Geology and Mineral Deposits of

MOUNT DIABLO

Contra Costa County, California

SPECIAL REPORT 80

California Division of Mines and Geology

Cover photo: View east along Arroyo del Cerro to Mount Diablo from the North Gate Road. Rolling slopes in foreground are underlain by Cretaceous sedimentary rocks; more rugged topography in background is carved on older and harder rocks. Grass-covered ridge on right skyline is Moses Rock Ridge; flat-topped brush-covered ridge on left skyline is Olofson Ridge. Saddle at left edge of Moses Rock Ridge is topographic expression of serpentine band that separates rocks of the Franciscan formation (right) from diabase (left). Summit of Mount Diablo is out of sight behind Moses Rock Ridge.

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MOUNT DIABLO

Contra Costa County, California

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ABSTRACT

This report deals with the geology of an area in Contra Costa County, about 25 square miles in extent, that includes Mount Diablo, a prominent northern California landmark. The oldest rocks are Upper(?) Jurassic sedimentary, igneous, and metamorphic units of the Franciscan formation, associated with intrusive diabase, pyroxenite, and serpentine. These rocks are unconformably overlain by sedimentary rocks of Upper Jurassic to Quaternary age that are themselves divided by numerous unconformities and cut by late(?) Tertiary rhyodacite bodies. Tertiary silica-carbonate rock is present in the vicinity of the rhyodacite, as well as a small amount of Recent travertine that overlies landslide and alluvial deposits. The most extensive structural feature is a northwest-trending anticline flanked by the post-Franciscan rocks. A plug of the older rocks, with the summit of Mount Diablo near its center, has been thrust upward into the crest of this anticline. The mechanism that caused the upthrusting has been explained in various ways by previous workers, and I am offering an explanation that differs in some particulars from any of theirs. It appears to me that the plug of older rocks, moving along shear planes lubricated by the serpentine, was thrust upward through the sedimentary cover by regional compressive forces related to the San Andreas fault system. The unconformities in the younger sedimentary section show that the upward movement continued intermittently from Early Cretaceous to Recent time. Similar piercement structures have been reported elsewhere in the Coast Ranges.

Mining in this area began in the early 1860's with the discovery of silver, gold-bearing copper ores, and cinnabar in the older rocks. Between 1875 and 1957 more than $1,500,000 worth of mercury, together with some copper and small amounts of gold and silver, were produced. Reserves of low-grade quicksilver ore are known to exist in the Mount Diablo district, and with further exploration it might well be possible to discover new ore shoots. In recent years the principal mineral industry has been crushed stone quarrying, which from 1946 to 1957 has yielded stone products valued at more than $2,500,000.

Figure 1. Index map of the San Francisco Bay region showing location of the Mount Diablo area.

GEOLOGY AND MINERAL DEPOSITS OF MOUNT DIABLO, CONTRA COSTA COUNTY, CALIFORNIA

By Earl H. Pampeyan

INTRODUCTION

Mount Diablo is in the central part of the Coast Ranges, at the north end of the Diablo Range, which lies on the west side of the Great Valley of California. The area studied, which is roughly semicircular and covers about 25 square miles, includes Mount Diablo proper, North Peak, Eagle Peak, Mount Zion, and the lower slopes of these peaks (fig. 1). It is near the center of Contra Costa County and is readily accessible, being only about 40 miles by road east-northeast from San Francisco. Numerous private roads approach the base of the mountain, and paved roads lead from Walnut Creek and Danville to a State Park on the crest of the range. The highest point in the area is the summit of Mount Diablo, 3,849 feet above sea level; the lowest point, at an altitude of 420 feet, is west of Clayton, on the north edge of the area. The strongest relief—about 2,640 feet in a distance of 1.3 miles—is between the Mount Diablo mine and North Peak.

The climate is intermediate between that of Central California and that of the high Sierra Nevada. Summer temperatures of 100°-105°F are not uncommon around the mountain, and winter temperatures seldom are more than a few degrees below freezing. Light snows occasionally cover the mountain to altitudes as low as 1,000 feet on the north slopes, and the mean annual precipitation is about 25 inches at the summit.

Dense brush and forest cover much of the area, especially the north-facing slopes, but there are some large grass-covered areas, generally underlain by landslides, on the lower south-facing slopes of Mount Diablo. Trees and shrubs common in the district include buckeye, oaks of at least three varieties, manzanita, toyon, and abundant poison oak; digger pines are less common. Because scrub oak, manzanita, and digger pine tend to be concentrated in areas of magnesian soils derived from serpentine, their distribution aided in locating small serpentine bodies. The wild animals on the mountain are chiefly rabbits and other small rodents, snakes, raccoons, and deer; bobcats are occasionally seen, and infrequently a mountain lion.

The early history of Mount Diablo and the surrounding country is enlivened by stories of Indians, Spanish explorers, and mining booms. There are numerous legends concerning the names formerly applied to the peak now called Mount Diablo, and some of these are reported by Purcell (1940). According to Gudde (1949, p. 94) the earliest recorded name for the mountain was "San Juan Bautista," which was bestowed in 1790, probably in honor of Don Juan Bautista de Anza, who in 1776 visited the coal mines 5½ miles north of the main peak. Purcell (p. 59), however, says that members of Don Juan's party referred to the main peak as "Sierra de los Bolgones," after the Indians who lived around it. The origin of the name "Mount Diablo" is related by General M. G. Vallejo (1850, p. 529-530) as follows:

> "In 1806 a military expedition from San Francisco marched against the tribe of the 'Bolgones', who were encamped at the foot of the Mount; the Indians were prepared to receive the expedition, and a hot engagement ensued in the large hollow fronting the western side of the Mount. As the victory was about to be decided in favor of the Indians, an unknown personage, decorated with the most extraordinary plumage, and making divers movements, suddenly appeared near the combatants. The Indians were victorious and the incognito (Puy) departed towards the Mount. The defeated soldiers, on ascertaining that the apparition went through the same ceremony daily and at all hours, named the mount 'Diablo', in allusion to its mysterious inhabitant, that continued thus to make his strange appearance until the tribe was subdued by troops in command of Lieut. Gabriel Moraga, in a second campaign of the same year."

Monte Diablo, and later Mount Diablo, was established by American explorers in the 1840's as the name for the main peak, though the old inhabitants of the region say this name was originally applied only to what is now called North Peak.

Because of the great height of the main peak as compared with the surrounding hills, and its geographic location along the west edge of the Great Valley, such distant features as Mount Lassen, to the north, and Yosemite Valley, to the east, are visible from its summit on clear days. For this reason the summit was established in 1851 by Leander Ransome, for the Surveyor General of California, as the initial point of the Mount Diablo Base Line and Meridian. The land net based on this point is used in about two-thirds of California and all of Nevada.

In 1860, claims containing silver ore were located on the northwest side of Mount Zion, and three years later copper ores containing traces of gold were discovered on the slopes of Eagle Peak, Black Point, and Mount Zion (Pyramid Hill). The numerous prospect holes in this area show how actively these ores were worked, but only a small production of copper and silver was recorded. At some time between 1863 and 1864 cinnabar was discovered on the northeast slope of North Peak, near the future site of the Ryne mine, and between 1875 and 1877 several thousand dollars worth of quicksilver was produced. Quicksilver mining has gone on intermittently in the Mount Diablo district since that time, and has produced more than $1,500,000 worth of quicksilver. This has constituted the only metal-mining industry in the area during recent years. In 1957 no quicksilver was being mined, and the only mineral product of the area was crushed stone, taken from two quarries south of Clayton, on the east and west slopes of Mount Zion.

Previous geologic studies in this area are numerous; only the more significant ones are noted below. The first published description of the geology of Mount Diablo is by J. D. Whitney (1865), in his account of the Coast Ranges of California. About 25 years later H. W. Turner (1891; 1898) made a detailed study of Mount Diablo and the surrounding area, which resulted in the first published geologic map of this area. In 1935 J. A. Taff published a description of the stratigraphy and structure of parts of the Mount Diablo and Byron quadrangles. Professors B. L. Clark and G. D. Louderback of the University of California each prepared maps of the mountain, but only a part of Clark's map was published. The most recent report on this area was by C. P. Ross (1940), who described the quicksilver deposits on the northeast flank of North Peak.

The Mount Diablo area was mapped by the U. S. Geological Survey, in cooperation with the California Division of Mines, during February of 1957. The present report is based mainly on this mapping, but also includes field work carried on intermittently in the Mount Diablo quicksilver district from 1952 to 1956, in a study of quicksilver deposits for the Geological Survey and the Defense Minerals Exploration Administration. The area containing the quicksilver mines was surveyed on a scale of 100 feet to the inch, and the surrounding areal geology was mapped on a scale of 1:24,000 on adjoining parts of the Clayton, Diablo, Antioch South, and Tassajara 7½-minute topographic quadrangle maps of the U. S. Geological Survey.

Many property owners kindly granted access to their land. Mr. Worthen Bradley of the Bradley Mining Co., Mr. J. E. Gilbert of the Cordero Mining Co., and Mr. Vic Blomberg of the Mount Diablo Quicksilver Mines Inc., Ltd., were very helpful in supplying historical facts and mine maps. The H. J. Kaiser Co. and the Pacific Cement and Aggregates, Inc. Company allowed access to their quarries and information on their operations. Personnel of the California Division of Beaches and Parks were helpful in allowing access to roads in the Mount Diablo State Park. J. F. Robertson and D. B. Tatlock of the U. S. Geological Survey assisted with the plane table mapping of the quicksilver district during January of 1953, and H. G. Stephens of the Survey aided with the mapping of the boundary fault for a brief period in 1954. Others who contributed data for this report include F. N. Ward, C. H. Sandberg, and W. T. Kinoshita of the U. S. Geological Survey, and F. F. Davis and H. B. Goldman of the California Division of Mines.

GENERAL GEOLOGY

The Coast Ranges of California east of San Francisco consist of Mesozoic and Cenozoic rocks, folded into a series of northwest-striking anticlines and synclines that are in some places overturned to the west. The Diablo Range, which forms the east edge of the Coast Ranges, is made up of a number of folds lying en echelon for more than 150 miles south of the Bay Area; Mount Diablo is at the north end of the Diablo Range and on the crest of one of these anticlines. The rocks of Mount Diablo and vicinity can be divided into four groups: (1) a basement complex of broken and jumbled sedimentary, igneous, and metamorphic rocks; (2) a section of younger sedimentary rocks, more than 35,000 feet thick, in fault contact with the basement complex; (3) volcanic rocks which locally cut and overlie the younger sedimentary rocks; and (4) landslides, alluvium, and travertine which in places cover the older rocks.

The rocks of the basement complex make up the main mass of Mount Diablo, which occupies an area of about 18 square miles (pl. 1). They are in fault contact with the surrounding sedimentary rocks and form a semicircular plug which has been upthrust through the overlying strata. This plug is divided into two parts by a narrow northeast-trending band of serpentine. South of this band, greenstone, chert, graywacke, shale, limestone, schist, and conglomerate of the Franciscan formation, cut by a few small bodies of serpentine, crop out in an area of 11 square miles. North of the serpentine band, an area of 5½ square miles is occupied mainly by diabase but includes a few exposures of pillow basalt and vesicular diabase. The exact age relations of the rocks composing the basement complex are unknown; but it appears that first the diabase and then the serpentine intruded the Franciscan rocks before the plug was emplaced.

The sedimentary rocks overlying the basement complex consist mainly of fossiliferous clastic marine beds ranging in age from Late Jurassic to late Miocene, but fresh-water Pliocene deposits overlie the Miocene beds south of Mount Diablo (pl. 2). On the northeast side of Mount Diablo, Cretaceous rocks are cut by dikes and plugs of rhyodacite probably of late Tertiary or early Quaternary age. South and east of Mount Diablo, along the periphery of the plug, numerous recent landslides obscure much of the bedrock geology. Table 1 shows the stratigraphic sequence of the rocks in the area.

Rock Units

UPPER(?) JURASSIC ROCKS

Franciscan formation

Rocks of the Franciscan formation underlie the main peak of Mount Diablo and North Peak. These rocks consist of contorted thin-bedded chert, greenstone, and graywacke, with minor interbeds and lenses of shale, conglomerate, limestone, and schist. All the rocks are highly fractured, and are criss-crossed with veinlets of quartz and carbonate. Greenstone and chert occupy about 75 percent of the area, graywacke about 20 percent, and shale, schist, conglomerate, and limestone the remainder. Local dense brush cover and landslides made it impracticable to map out the different rock types in the allocated time. Their stratigraphic relations, moreover, are obscured by the intense deformation they have undergone. Even where exposures are good it is difficult to find a section more than 25 feet thick that is not broken by faults so closely spaced as to preclude mapping on a scale of 2,000 feet to the inch. Neither the top nor the base of this unit has been recognized, so that its thickness is unknown. The age of the Franciscan rocks exposed is in doubt, but they cannot be younger than Late Jurassic, for they are in fault contact with an unbroken and unmetamorphosed section of fossiliferous rocks ranging in age from Late Jurassic (Portlandian) to Pliocene, none of which resemble any of the Franciscan rocks.

Greenstone. Greenstone, forming characteristic rugged outcrops, underlies much of North Peak and the summit of the main peak. More than one igneous or meta-igneous rock type is included under the general term greenstone, but in this area submarine lava, or pillow basalt, and fine-grained diabase predominate. The pillow structure is apparent only in relatively few exposures; locally, however, it is well defined and can be used to determine the tops of beds. Individual pillows are commonly surrounded by a dense "rind" of chlorite rock ¼ to ¾ inch thick. The pillows are from 4 to 18 inches in diameter, those in any given outcrop being fairly uniform in size. Fine-grained diabase occurs in moderate amounts in the area of Franciscan rocks, and in the field it is difficult to distinguish from the pillow basalt. Vesicular diabase also occurs in a few of the greenstone outcrops. It is usually greenish-black (5 GY 2/1)*, and the vesicles, 2 to 4 mm in diameter, are conspicuous because they are mainly filled with white calcite.

In most exposures the greenstone is highly weathered, forming soils that range in color from dark yellowish-brown (10 YR 4/2) to dark reddish-brown (10 R 3/4); but in some places the greenstone resists weathering and forms knobs, ridges, and cliffs. Its color on fresh surfaces ranges from grayish-green (5 G 5/2) to light olive-gray (5 Y 5/2).

Under the microscope all the non-vesicular greenstones are seen to be similar in composition; they differ chiefly in texture and grain size. The rocks are composed of augite almost completely altered to chlorite and serpentine minerals; andesine laths mostly albitized or altered to clay minerals, epidote, and calcite; and some iron oxides and sulfides.

The vesicular rock is found to consist of a network of plagioclase laths or microlites in a microcrystalline groundmass of chlorite, granular ilmenite, and epidote; the feldspar is commonly albitized or saussuritized, but unaltered phenocrysts of oligoclase are present locally. The filled vesicles commonly have a thin outer rim of chlorite or quartz or both and a core of calcite, but some are filled with calcite, quartz, and epidote. In general the vesicular rocks correspond to the spilites described by Williams and others (1954, p. 58).

Similar rocks crop out in the diabase area north of the serpentine band. Chemical analyses of greenstones from Mount Diablo and other Coast Range localities, by W. M. Melville, are included in the papers by Turner (1891; 1898).

Chert. Large exposures of chert may be seen on the south face of Mount Diablo, along the North Gate and Summit roads in the State Park. Folds and fractures in the chert are readily apparent in the many road cuts. The color of this rock varies, on both fresh and weathered surfaces, from grayish-red (5 R 4/2) to pale-green (5 G 7/2) or white. Most of the chert is thin-bedded; the beds average an inch and a half in thickness and are separated by layers of laminated shale, of the same color as the chert, that range from paper-thin to serveral inches in thickness but average about ⅛ inch. The ratio of chert

* Color symbols used are from Goddard (1948).

Table 1. Geologic units of the Mount Diablo area.

Geologic age: Era	Period	Epoch	Approximate age (myo *)	TAFF (1935) Sedimentary	TAFF (1935) Igneous, metamorphic	JENKINS ET AL. (1951, p. 163) Sedimentary	JENKINS ET AL. (1951, p. 163) Igneous	THIS REPORT Sedimentary	THIS REPORT Igneous, metamorphic	Symbol on pl. 2
CENOZOIC	Quaternary	Recent	0-1	Landslides; alluvium		Valley and terrace alluvium; travertine		Travertine Alluvium Landslides		Qt Qal Qls
		Pleistocene			Basalt		Basalt			
	Tertiary	Pliocene	1-12	Orinda formation San Pablo formation	Pinole tuff	Los Medanos formation Tassajara formation Green Valley formation Alamo formation Orinda formation	Lawler tuff (Pinole tuff)	Undifferentiated Upper Jurassic to Tertiary sedimentary rocks	Rhyodacite in Marsh Creek Springs area Silica-carbonate rock	Tr Tsc
		Miocene	12-18	Undifferentiated Miocene		San Pablo group Neroly sandstone Cierbo sandstone Brinoes sandstone Temblor (Monterey) formation	Kirker tuff			
		Oligocene	28-40	Kreyenhagen shale Markley formation		(San Ramon formation)				TKJ
		Eocene	40-60	Tejon group Domengine formation Meganos formation Martinez formation		Markley group Sidney shale Markley sandstone Nortonville shale Domengine (Tejon) Meganos formation Capay formation				
		Paleocene				Martinez formation				
		Position in Tertiary not determined			Andesite		Andesite			
MESOZOIC	Cretaceous	Late	60-130	Moreno formation Panoche formation Chico formation		Chico group Moreno formation Panoche formation				
		Early		Shasta formation		Shasta group Horsetown formation				
	Jurassic	Late	130-155	Knoxville shale		Knoxville formation				
		Late (?)			Franciscan series Serpentine Metamorphic complex and diabase and basalt	Franciscan group sandstone chert shale	Serpentine and greenstone	Franciscan formation (chert, graywacke, shale, limestone, conglomerate)	Diabase Serpentine and pyroxenite Schist (greenstone)	Jd sp py Jf, sch

The column on the extreme left shows standard geologic age name. The column on the extreme right shows symbols use on plate 2 of this report. Other columns show the names and approximate sequence of units as used by different workers in the Mount Diablo area.

*Million years ago by National Research Council on the Measurement of Geologic Time, 1949-1950.

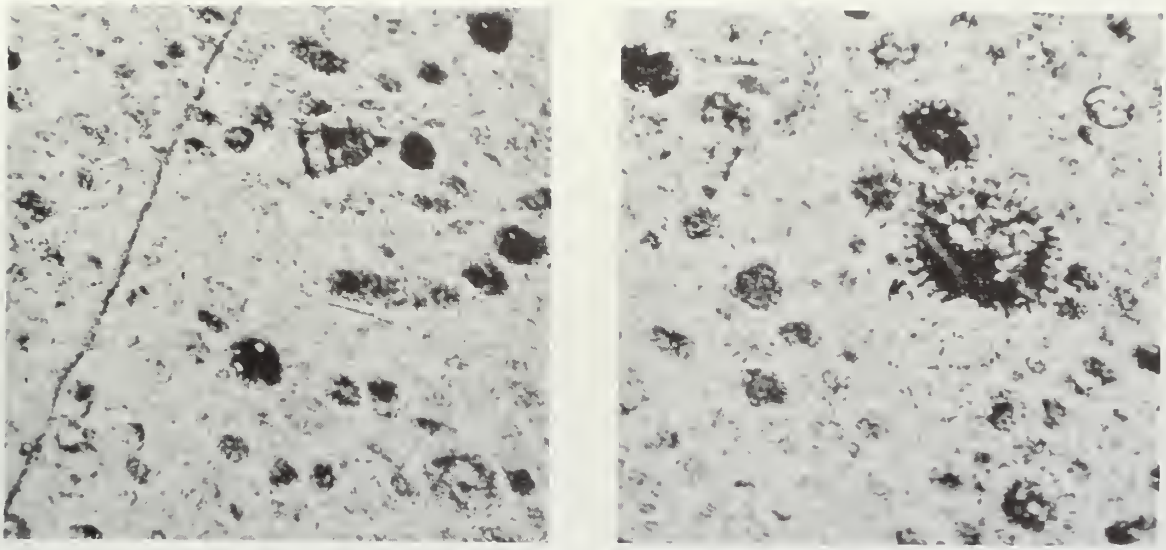

Figure 2. Photomicrographs of chert of the Franciscan formation showing sections of radiolarian tests. A. Dictyomitra(?) sp. B. Cenasphaera(?) sp. X 110. (Black and white reversed awning to dark-field illumination.)

to shale may range from 1:10 to 10:1 in a short distance along the strike. Chert with widely spaced shale partings is fairly resistant to weathering, but chert with abundant shale partings is easily weathered, yielding talus slopes of angular chert fragments.

The pale-green chert contains only a few shale partings, and forms lenses in greenstone derived from bedded pyroclastic materials. Lenses of white chert that are exposed locally are derived from red chert that has been recrystallized along fractures or faults.

Thin sections of red chert show numerous Radiolaria (fig. 2), but these are difficult to identify because of recrystallization of the tests. They show some resemblance, however, to the *Cenosphaera* sp. and *Dictyomitra* sp. described by Hinde (1894, figs. 1, 15, 16) and the *Dicolocapsa* sp. and *Dictyomitra* sp. described by Riedel and Schlocker (1956, figs. 3, 7). These species have not yet proved useful in dating the beds.

Graywacke and shale. Outcrops of dark, poorly sorted, dirty sandstone, or lithic graywacke (Williams and others, 1954, p. 294), occur throughout the area of Franciscan rocks but do not constitute a large part of the Franciscan formation in the Mount Diablo plug. The best exposure of graywacke is in the Bradley rock quarry in sec. 29, T. 1 N., R. 1 E., where indurated graywacke was quarried for riprap. The graywacke shows considerable variation in physical characteristics, partly owing to later deformation and mild metamorphism. Typically it is fine- to medium-grained, moderate greenish-gray (5 G 5/1) to dusky yellow-green (5 GY 5/2) on fresh surfaces and yellowish-brown (10 YR 5/5) to dark greenish-gray (5 GY 4/1) on weathered surfaces, and shows little evidence of bedding. Numerous veinlets of quartz and carbonate criss-cross the graywacke. Some of the graywacke is indurated and resists weathering, but most of it weathers easily to smooth rounded slopes. The principal constituents of the grains, most of which are sharply angular, are quartz, andesine, chert, and dark volcanic rocks; these, together with a few flakes of black shale, are embedded in a matrix of chlorite and clay minerals. The rock does not contain any K-feldspar—a fact that helps to distinguish it from similar rocks in the Knoxville formation (p. 15).

Turner (1898, p. 492) describes a fossil locality in graywacke of the Franciscan about 1 mile northeast of North Peak. Merriam (1915), however, reports that the fauna collected there, though apparently marine, consisted of forms that did not indicate the age of the rocks.

Thin lenticular interbeds of black shale, commonly sheared, occur locally in the graywacke, as do small fragments or flakes of shale; both features help in some places to distinguish bedding planes in the enclosing rocks.

Conglomerate and limestone. Outcrops of conglomerate were seen at two localities: the first is on the northwest side of North Peak, on the spur north of Wild Oat Canyon; the second is on the southeast side of the main peak, in the center of sec. 5, T. 1 S., R. 1 E. At both places the conglomerate consists of well-rounded pebbles and cobbles of indurated shale, greenstone, black and white banded chert, quartzite, and basic volcanic rocks, in a graywacke matrix. Neither outcrop can be traced very far along the strike, but the one in section 5 (described by Davis, 1918, p. 25) shows a succession of poorly sorted, well cemented beds about 25 feet thick. Like the graywacke, the matrix, pebbles, and cobbles of the conglomerates contain no K-feldspar.

A small quantity of limestone, in thin discontinuous beds or lenses 2 to 4 inches thick and several feet long, is interbedded with the chert and greenstone. This rock is grayish-red (5 R 4/2) both on weathered and fresh surfaces, is very fine-grained, and is easily mistaken for chert. Specimens of the limestone in greenstone collected on North Peak contain foraminifera, but these are too poorly preserved to be identified.

Schist. Schistose rocks derived from sedimentary and igneous rocks of the Franciscan formation crop out south of the serpentine band. Most of these rocks contain glaucophane but many of them do not; the best exposures of glaucophane schist are shown in plate 1. The glaucophane shists are easily recognized by their characteristic dusky blue color (5 PB 3/2) on both weathered and fresh surfaces; this is especially striking when the rock is wet. Other schists in this area include quartz-sericite schist with traces of chlorite and epidote, actinolite-talc schist, and garnet-stilpnomelane-muscovite-quartz schist. Glaucophane, quartz, muscovite, garnet, chlorite, epidote, actinolite, and calcite are the principal constituents in most of these schists; albite, pumpellyite, stilpnomelane, and lawsonite are also present but only in small amounts. Some fractures in the schistose rocks are thinly coated with manganese and copper minerals.

The mica-quartz and actinolite schists weather easily and form subdued outcrops. The glaucophane schist, however, is resistant to weathering, and commonly forms bold outcrops and large rugged boulders up to 30 feet in diameter. Owing to its resistant character and its pleasing color, glaucophane schist has been used for building stone in and around the Mount Diablo area.

In this district as elsewhere in the Coast Ranges the Franciscan rocks were changed by metasomatic activity localized along certain favorable structural or lithologic zones. The origin of the sodic emanations responsible for the changes is not known, but they probably came from some deep-seated source (Williams and others, 1954, p. 225). The metamorphic activity apparently preceded Knoxville time, for no metamorphic effects were seen in the Knoxville and younger sedimentary rocks surrounding Mount Diablo.

Diabase

North of the serpentine band, the brush-covered peaks are underlain by crystalline rocks which are shown on plate 1 as diabase. Almost all the outcrops consist of dusky yellow-green-weathering (5 GY 5/2), dark greenish-gray (5 G 4/1), massive ophitic diabase, whose average grain size ranges from ½ to 2 mm; the remainder consist of dusky yellow-weathering (5 Y 6/4) pillow basalt and grayish-green (5 G 5/2) vesicular diabase. The diabase consists mainly of labradorite, secondary hornblende, chlorite minerals, and augite; it also contains small amounts of ilmenite, pyrite, calcite, albite, and sericite. The numerous samples of diabase collected north of the serpentine band all appear to be of the same type, with only minor variations in grain size and alteration. The diabase, the pillow basalt, and vesicular diabase north of the serpentine band seem remarkably similar in texture and composition to the greenstones in the area of Franciscan rocks. This similarity holds true even in thin section.

Joints in the diabase generally strike and dip in all directions, though in some small areas the attitudes are fairly regular. Apparently the diabase is just as broken and jumbled as the Franciscan rocks, but its homogeneity hides all but the major breaks. In places the diabase along the joints grades into a black aphanitic rock, which is seen under the microscope to be a chlorite-rich microcrystalline diabase. This rock passes irregularly, toward the joints, into an ilmenite-chlorite rock, apparently formed from the diabase by intense alteration.

The diabase is thought to be intrusive, even though some of it has features that suggest extrusion. Intrusive origin is indicated by the uniformity of composition of the diabase throughout the area, the absence of chert, shale, and tuffaceous or other clastic sediments in a section apparently more than 1,500 feet thick, and the shape of the contact between diabase and serpentine. Extrusive origin is suggested, on the other hand, by the presence of pillow basalt and vesicles in some of the diabase, the absence of chilled margins around the diabase and of thermally altered zones in the enclosing rocks, and the similarity of the igneous rocks on the two sides of the serpentine band. These facts might be interpreted as evidence that the diabase and Franciscan rocks represent displaced members of a succession of extrusive igneous and clastic rocks separated by serpentine along a fault zone. They can be explained, however, by assuming that the few outcrops of pillow basalt and vesicular diabase represent remnants or xenoliths of the rocks into which most of the diabase was intruded; that igneous contact phenomena between diabase and sedimentary rocks are lacking because in most places these rocks are in fault contact; and that the fine-grained diabase in the area of Franciscan rocks represents dikes or plugs of the intrusive rock. It is also quite probable that post-intrusion movement along the serpentine band has obliterated any pre-existing evidence of intrusion.

The diabase is younger than the Franciscan formation, but its relation to the Knoxville formation is not known. About 1 mile south-southwest of Clayton, however, some poorly exposed mudstone resembling that in the Knoxville apparently overlies diabase, indicating that the intrusion is older than the Knoxville.

Serpentine and pyroxenite

Serpentine, a rock formed by the hydration of ultramafic igneous rocks, forms a large dike-like body separating the areas of diabase and Franciscan rocks, and small irregular bodies within the area of Franciscan rocks. It is pale-green (5 G 7/2) to greenish-black, (5 G 2/1) on fresh fracture, and weathers to grayish-orange (10 YR 7/4), forming rounded boulder-covered slopes. In fresh exposures it consists of a small proportion of partly serpentinized peridotite blocks in a matrix of highly foliated serpentine, broken into countless fragments with shiny curved surfaces, in which the original igneous textures have been completely destroyed. The partly serpentinized peridotite blocks commonly exhibit a holocrystalline igneous texture, and some of the original olivine as well as pyroxene are relatively unaltered. Minerals making up the serpentine include antigorite, ortho- and clinopyroxene, chromite, magnetite, opal, chlorite, and carbonate minerals; chrysotile in thin veinlets is abundant.

On Long Ridge, near the western end of the large serpentine band, an area of about one-eighth of a square mile is covered with pieces of coarse-grained pyroxenite. None of this rock was seen in place, but it probably underlies this area. The rock is pale reddish-brown (10 R 5/4) on weathered surfaces and dark grayish olive-green (5 GY 3/2) on fresh surfaces; it consists almost entirely of hypersthene and augite, but contains a little chromite, magnetite, and scarce residual grains of olivine surrounded by serpentine minerals. The pyroxene grains are from 4 to 14 mm in diameter and average 6 mm.

Small outcrops of pyroxenite also occur in the narrow serpentine tongue west-southwest of Peach Tree Springs and north of the Arroyo del Cerro, which Turner (1898, p. 490) believed to represent a dike intrusive into shales of the Knoxville formation. The serpentine does cut across the bedding of the sedimentary rocks at this locality, but the rocks in contact with it are neither indurated nor metamorphosed. The contacts, moreover, between the ultramafic rocks and the enclosing rocks, wherever they were seen, are sheared, suggesting emplacement by "cold" intrusion.

The serpentine is certainly younger than the Franciscan rocks that it cuts, and it may be younger than the diabase which it separates from the Franciscan rocks. It may be older than the Knoxville formation or the rocks of Early Cretaceous age, even though the serpentine tongue in the Arroyo del Cerro does intersect those rocks. This tongue, and probably part of the large serpentine mass, may consist of serpentine that was smeared out along a fault by the upthrusting of the plug after the serpentine was emplaced in the Franciscan rocks.

UPPER JURASSIC TO TERTIARY ROCKS

Undifferentiated Upper Jurassic to Tertiary sedimentary rocks

All the unmetamorphosed marine sedimentary rocks on the flanks of Mount Diablo have been mapped as a single unit on plate 1, but the distribution of the subdivisions made by other geologists is shown on plate 2. These rocks rocks range in age from Upper Jurassic (Knoxville formation) to Miocene (San Pablo group). I did not study them, and shall therefore discuss them only briefly in this report. Those interested in the Mesozoic or Cenozoic stratigraphy in this region will find it discussed more fully in papers by Turner (1891; 1898), Clark and Woodford (1927), Clark (1935), Taff (1935), Clark and Campbell (1942), and Weaver (1949). Stratigraphic data on Upper Jurassic to Tertiary rocks will now be summarized, however, in order to provide the reader with an adequate background of the geologic setting of the Mount Diablo area. They have been taken principally from Taff (1935), but the nomenclature here applied to these rocks is that of Jenkins (1951, p. 163) (table 1).

Although Mount Diablo is in the core of an anticline, the stratigraphic sections on the two sides of the mountain are somewhat different (fig. 3). The lower part of each section appears to be the same, consisting of beds of the Knoxville unconformably overlain by beds of Lower Cretaceous age. Northeast of Mount Diablo, however, the total thickness of the beds above this unconformity is about 32,000 feet, whereas southwest of the mountain, less than 12 miles away, it is only about 12,000 feet. This great difference is probably due chiefly to the fact that both sections are broken by numerous angular unconformities, representing periods of uplift and erosion, but it is probably also in part due to faulting. The beds on the northeast flank of the anticline dip, in general, about 40° northeast; those on the southwest flank dip steeply to the southwest and are locally overturned.

The oldest sedimentary unit outside of the plug is the Knoxville formation, which crops out on the west and north sides of Mount Diablo. It consists of a hackly dark mudstone with interspersed lenses of limestone 2 to 3 inches thick and some sandy beds; this lithology is characteristic of the Knoxville in other parts of the Coast Ranges. Fossils found in limy concretions in Donner Canyon (NE¼ sec. 25, T. 1 N., R. 1 W.) and also in the old Harrison-Birdwell quarry (SE¼SW¼ sec. 14) in fault gouge separating beds of the Knoxville from diabase, were identified by D. L. Jones of the U.S. Geological Survey (written communication, 1958) as *Buchia piochii* (Gabb), a species restricted to rocks of Late Jurassic (Portlandian) age.

Beds of Early Cretaceous age (Shasta formation of Taff, fig. 3), stratigraphically above the Knoxville, crop out all around the mountain. They and the succeeding

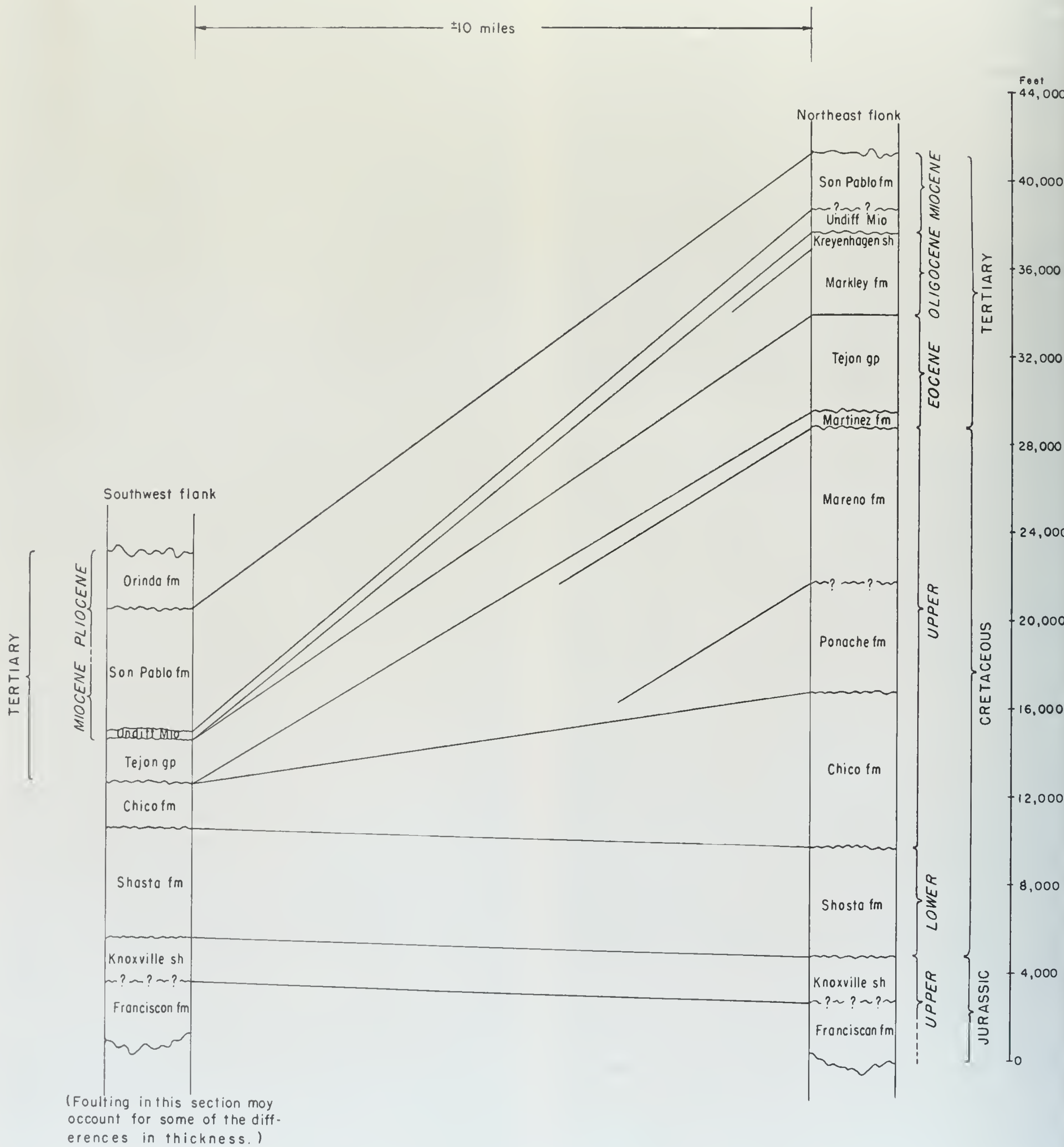

Figure 3. Comparison of columnar sections on the northeast and southwest flanks of Mount Diablo. (Adapted from Taff, 1935.)

Cretaceous formations are mostly shaly mudstones and arkosic sandstones, but there are sparse limestone lenses and concretions in the shales and conglomerate lenses at the base of each formation. The upper part of this section, the Moreno formation, however, consists mostly of quartzose sandstones and clay shales. Here as in the northern Coast Ranges (Bailey and Irwin, 1957), clastic rocks of the Knoxville and younger formations can be distinguished from graywackes of the Franciscan by the presence of from 10 to 15 percent K-feldspar in the younger rocks.

The Tertiary formations contain a large variety of sedimentary rock types that include conglomerate, glauconitic, conglomeratic, arkosic, and quartzose sandstones, diatomaceous and tuffaceous shales, shales with limestone lenses, clay shale, and coal. On the north side of Mount Diablo the Domengine formation (upper part of the Tejon group of Taff, fig. 3) has economic significance, for it contains a quartz sandstone member 500 feet thick with minor interbeds of shale and two beds of coal. The standstone is excavated locally for use as foundry sand. Coal was produced from mines at Nortonville, Somersville, and Stewartsville (Turner, 1891, p. 392). South of Mount Diablo little or no coal exists in the Domengine and the formation consists of massive sandstone which crops out between South Gate and Buckeye Camp (pl. 1) of the State Park. Stratigraphically above the Eocene beds are highly fossiliferous conglomeratic sandstones of the Miocene San Pablo formation. The public buildings at the summit of Mount Diablo are made of stone taken from a small quarry in the San Pablo at the South Gate of the park. Overlying the San Pablo is the Pliocene Orinda formation which consists of conglomerate sandstone, limestone, and clay of fresh or brackish water origin. Interbedded with these Miocene and Pliocene formations are light-colored to white beds of tuffaceous and bentonitic shales, evidence that volcanic activity occurred at this time.

Taff (1935, p. 1091) describes a conglomerate member in the upper part of his Tejon group (upper Eocene) on Lime Ridge, 2 miles west of Mount Zion, and also at Nortonville, 4½ miles north of North Peak. This conglomerate contains pebbles and cobbles of diabase resembling the diabase that underlies the Mount Zion-Eagle Peak area, which indicates that the diabase was locally uncovered by erosion in late Eocene time. As detrital Franciscan material has not been described from other sedimentary formations of this region, the Mount Diablo basement complex probably was not exposed to erosion, except for this brief period, until Pleistocene or Recent time.*

* According to E. C. Morris (oral communication, July 1961), heavy mineral studies of the Eocene formations on the north side of Mount Diablo indicate that probably no Franciscan rocks near the present site of Mount Diablo contributed debris to the sediments during Eocene time.

Silica-carbonate rock

Silica-carbonate rock, the principal host rock for the quicksilver deposits, crops out at the eastern end of the serpentine band, in the vicinity of the Mount Diablo and Ryne mines. It was formed by hydrothermal alteration of serpentine, and is composed, as the name implies, of varying amounts of quartz, chalcedony, and opaline silica, together with ferroan dolomite and other carbonates. Small amounts of unaltered magnetite and chromite that were accessory minerals from the original ultramafic rock remain in the rock. The silica-carbonate rock varies widely in texture: some of it consists of paper-thin laminae, while some is dense, massive, and irregularly banded. These textures are probably inherited in part from the sheared serpentine, for in places the silica-carbonate rock grades into unaltered serpentine. Weathering of the silica-carbonate rock commonly results in a rusty-colored spongy or porous rock that consists mainly of iron-stained silica.

Rhyodacite

In the vicinity of Sunshine Camp, east-northeast of North Peak, a group of volcanic plugs cut beds of Lower Cretaceous age. Only a few of the plugs are shown on plate 1; others lie near a line trending slightly east of south through Marsh Creek Springs (pl. 2). The contact relations are generally obscure, but one cylindrical body south of Sunshine Camp cuts across the bedding of the Cretaceous shales and is surrounded by an indurated zone ten feet wide. Another plug at the mouth of Perkins Canyon (pl. 1) intrudes Cretaceous beds along the fault contact with Franciscan rocks. The rock here is cut by calcite veinlets, containing small amounts of sulfides of mercury and iron.

This rock was called a micaceous hornblende-andesite by Turner (1891, p. 393), and by Taff (1935, p. 1094), Ross (1940, p. 35), and others who followed Turner's usage. A study of thin sections and hand specimens shows a micro- to cryptocrystalline groundmass dotted with phenocrysts of zoned plagioclase, biotite, and hornblende, but with X-ray diffraction and staining techniques samples from these plugs were found to contain about 30 percent quartz, about 35 percent K-feldspar, mostly as orthoclase but including some sanidine and microcline, and about 25 percent plagioclase (An_{32-35}). As much as 20 percent of some samples consists of biotite, hornblende, and kaolinite; small amounts of calcite, chlorite, magnetite, apatite, and epidote also are present. According to the classification scheme of Williams, Turner, and Gilbert (1954, p. 126) these volcanic rocks are better named rhyodacites.

About 3 miles northwest of Clayton (pl. 2) basalt flows overlie Oligocene strata and are overlapped by Recent gravels (Taff, 1935, p. 1094). The rhyodacite and basalt may be related and both may be of late Tertiary age. N. L. Taliaferro (oral communication, 1957) compares these volcanic rocks with others in the central Coast Ranges that are as young as Pleistocene; perhaps they are nearly contemporaneous with the Leona rhyolite in the Berkeley Hills.

QUATERNARY DEPOSITS

Landslides

Landslide deposits of moderate areal extent, a few inches to 35 feet or more in thickness, overlie the previously described formations, especially on the north, east, and south slopes of the Mount Diablo plug. These deposits consist principally of poorly sorted angular fragments of Franciscan rocks and serpentine, ranging from clay-size particles to blocks 30 feet in diameter. In many places it is difficult to distinguish landslide deposits from bedrock, but usually the hummocky topography of landslide areas can be recognized in the field, on aerial photographs, or even on topographic maps.

Alluvium

Recent alluvial deposits cover the low slopes and creek bottoms along the north and east sides of the Mount Diablo mass. The deposits are poorly sorted and contain clay- to cobble-sized fragments of all the rocks being eroded at this time. Most of the alluviated areas are under cultivation.

Travertine

Travertine occurs at two places in the vicinity of Mount Diablo, one near the Mount Diablo quicksilver mine and the other west of Mount Zion. About 500 feet east of the Mount Diablo mine the lower end of a travertine deposit can be seen to overlie Cretaceous beds and Quaternary landslides and alluvium. Although the deposit is now mostly covered with waste from the mine, it originally measured 600 by 200 feet (Knox, 1938, p. 26). The rock is yellowish-gray (5 Y 8/1), porous, and layered parallel to the gentle slope on which it lies.

On Lime Ridge, west of Mount Zion and outside of the mapped area, flat-lying travertine deposits more than 20 feet thick overlie steeply-dipping Eocene beds in an area about 2½ miles long and half a mile wide. The travertine is very dense, and some of it shows concentric layering.

No active springs were seen at either of these localities, but a small flow of water over the travertine deposit near the Mount Diablo mine was noted. The source of this water is uncertain, because it is now covered with waste.

Structure

The geologic map of Mount Diablo and vicinity (pl. 2) shows a northwest-trending anticline of unmetamorphosed Jurassic to Tertiary rocks, pierced along its axis by a plug of highly disturbed sedimentary, metamorphic, and igneous rocks of the basement complex.

This relation constitutes what has come to be called a piercement structure—a term used frequently in California because this kind of structure occurs at several places in the Coast Ranges. The origin of piercement structures, and especially of the one centering near Mount Diablo, presents a problem that has aroused the interest of many previous workers in this area, each of whom has offered his own interpretation of the structure. A few have not regarded it as a piercement structure, but the majority have done so, even if they did not use the term. My reasons for regarding it as such are presented below.

The most important structural feature, in this regard, is the fault or fault zone bounding the core. Less pertinent, and probably less important, are the other faults, especially those within the core; and of prime importance, in my opinion, are the contacts of the serpentine with the surrounding rocks.

BOUNDARY FAULT

The rocks of the basement complex are separated from the Jurassic and younger rocks by what is here called the peripheral or boundary fault. This feature is on the whole a fault zone rather than a fault, for in most places it consists of highly sheared material up to 100 feet wide. West of Olofson Ridge and Mount Zion, however, it is a narrow fissure, probably because the core consists, there, of relatively homogeneous diabase. On the flanks of the main peak the boundary fault is largely obscured by landslides, and even where it is best exposed its attitude is hard to determine. West of Mount Zion the fault dips steeply to the west, away from the plug; in the Mount Diablo mine it dips 30° northeast at the surface and 70° northeast on the 360 level; along the east and west sides of the mapped area it is nearly vertical; and in the P. C. A. quarry it dips 65° east, away from the diabase. Along the south and southwest edge of the plug the attitude of the boundary fault is unknown, but the overturned beds exposed for several miles southwest of the mountain (Taliaferro, pl. 1, *in* Jenkins, 1951) indicate a component of movement of the plug to the southwest. It therefore seems likely that this part of the boundary fault dips northeast, or inward.

OTHER FAULTS

The area within the boundary fault is crossed by numerous faults, but owing to the nature of the rocks it was not possible to work out much of the internal structure of the core, and only a few faults are shown on plate 1. Only those faults were mapped that could be traced for considerable distances, either by direct observation of breccia and shear zones or by lining up gullies and saddles eroded along shear zones.

The Riggs Canyon fault, the northwest-trending fault described by Clark (1935), was not mapped during this study. On aerial photographs, however, it can be traced for several miles northwest of Riggs Canyon and at least a few miles southeast of it, separating the Eocene rocks from the Miocene rocks. Its approximate position is marked on plate 2.

SERPENTINE CONTACTS

All the exposed contacts between serpentine and the surrounding rocks are sheared, indicating either the "cold intrusion" type of emplacement, or movement after the serpentine was emplaced, or both. Most of the serpentine bodies extend along faults. In some places, however, the serpentine bodies do not conform with any local structure. The largest serpentine mass appears to follow a major fault zone, since it marks a clean break between the diabase on the north and the typical mixture of Franciscan rocks on the south. But, because of the lack of any horizon marker common to both sides, there is no way of estimating the amount and direction of whatever movement occurred along this zone.

PREVIOUS INTERPRETATIONS

Many papers discussing the structural interpretation of this geological setting have been published, each with different conclusions.

Turner (1891) did not recognize the fault separating the metamorphic and igneous rocks from the unmetamorphosed rocks, but he perceived that the Franciscan rocks had been metamorphosed before the deposition of beds of the Knoxville formation. He believed that upheaval and folding of the unmetamorphosed strata began in Miocene time, and that the main elevation of the metamorphic rocks occurred at the close of the Pliocene.

Louderback (1909), whose map of the Mount Diablo quadrangle was never published, described the structure in Mount Diablo as "an overturned and overthrust anticline of very late origin" (fig. 4).

Clark (1930) believed at first that the Franciscan rocks had been thrust westward over the Cretaceous rocks on a fault dipping gently eastward, but after further work in this area he realized (1935) that the basement rocks were upthrust through the Cretaceous rocks along high-angle faults. (The maps accompanying his papers, however, both show a flat fault with Franciscan rocks above and Cretaceous rocks below.) Clark did not recognize Louderback's major anticlinal structure, but attributed the steep and overturned dips of the Cretaceous and younger strata south of Mount Diablo to drag along a northwest-trending vertical fault, which he named the Riggs Canyon fault.

Bailey Willis (1936) believed that the structure of Mount Diablo was directly related to the San Andreas fault, that the core of the mountain was bounded by two northwest-trending faults which converged at depth, and that compression of the root squeezed the wedge-shaped block up through the overlying strata and thus initiated an anticline.

Taff (1935) believed that this plug of Franciscan rocks was forced upwards on essentially vertical shear planes by upward pressure of deep-seated origin, the upward movement being facilitated by progressive unloading of at least 20,000 feet of Cretaceous to Tertiary strata, and that faulting and folding of these strata proceeded at the same time.

AUTHOR'S INTERPRETATION

My own impression is that the basement complex was fractured and cut by serpentine dikes before the deposition of the Knoxville sediments, and was later subjected to lateral compression which forced a block of the basement rock obliquely upward (fig. 5). The block moved upward relative to sea level, in the direction of least resistance, along shear planes lubricated by the serpentine.

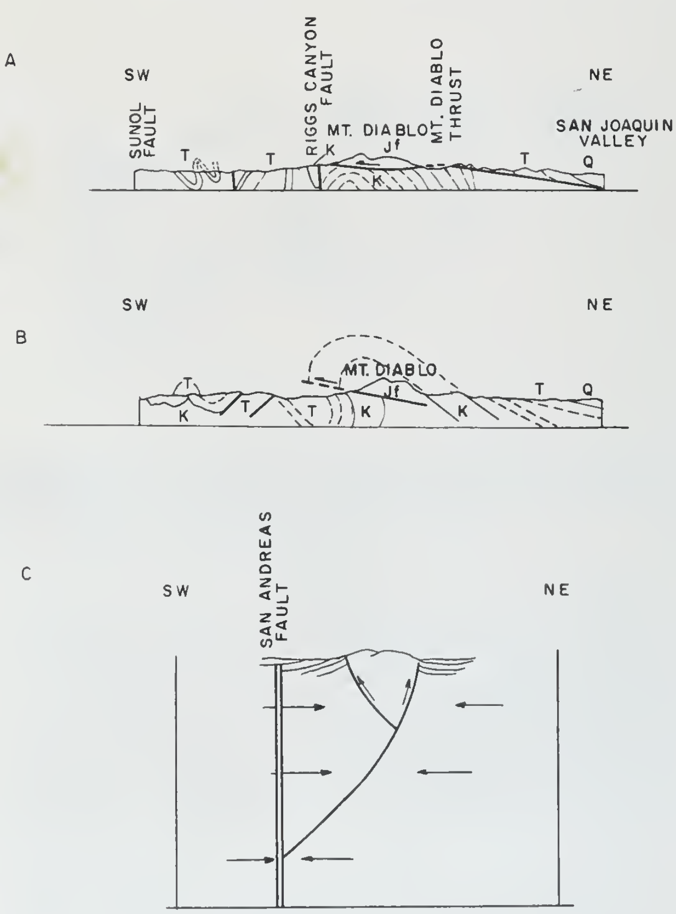

Figure 4. Previous structural interpretations of the Mount Diablo region. Redrawn from sections by: A, Clark (1930; 1935); B, Louderback (in Reed, 1933); C, Willis (1936). Q = Quaternary; T = Tertiary; K = Cretaceous; Jf = Franciscan formation.

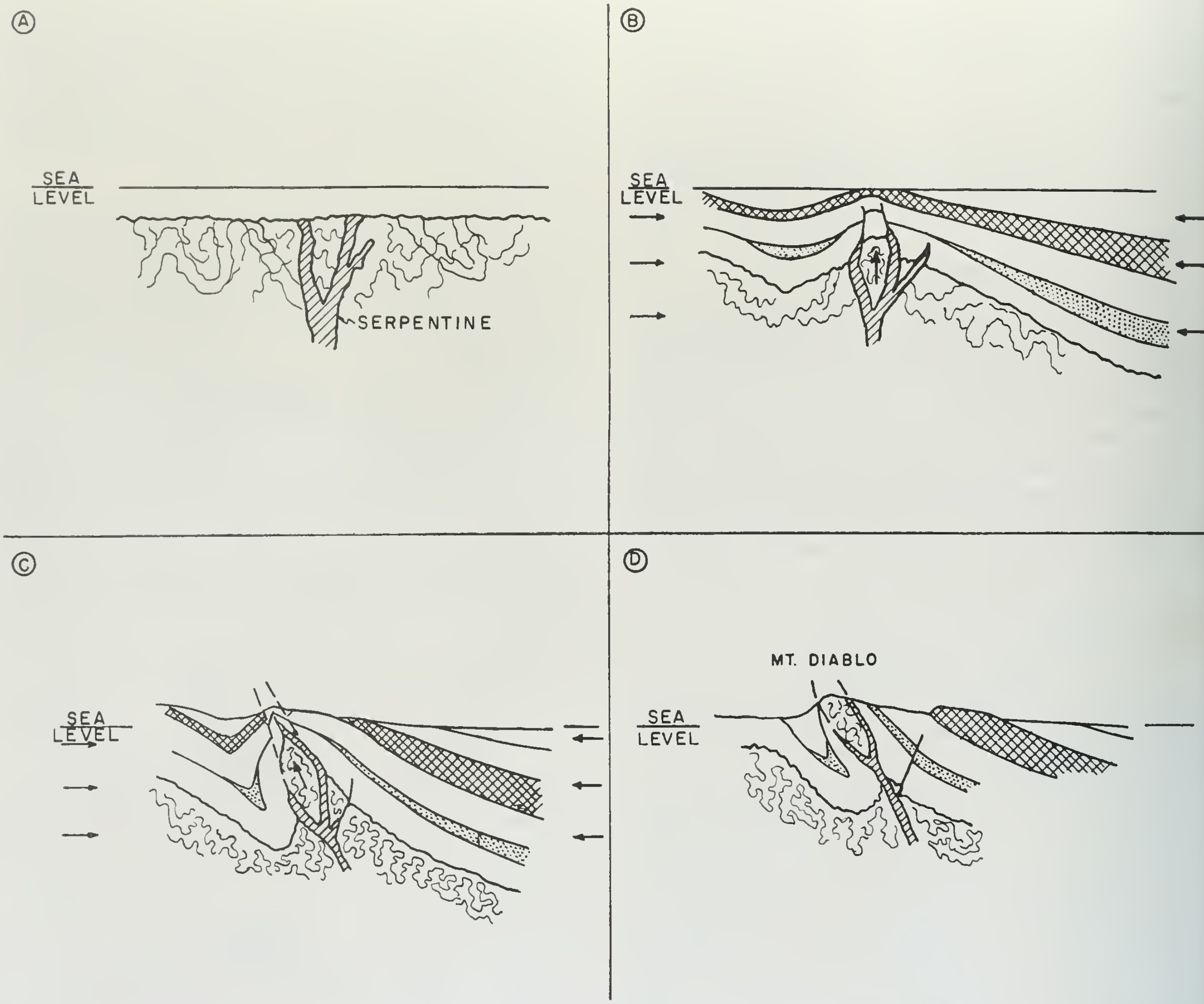

Figure 5. Hypathetical sequence of structural events in the Mount Diablo region. (Not to scale.) A. Basement complex was cut by serpentine dikes, eroded, and unconformably overlain by sediments. B. Lateral compression squeezed a plug of basement rocks and serpentine upward, initiating an anticline, while erosion and deposition created angular unconformities in the section. C. Compression continued to squeeze the plug upward through the overlying sedimentary section, locally thinned by erosion. D. Erosion exposed the plug and formed the present relief.

The presence of serpentine in the core appears to have been of major importance, for this rock, divided into numberless fragments with shiny curved surfaces, could have behaved like a plastic and acted as a lubricant in facilitating relative movement between the wall rocks. The fact that the serpentine is strongly slickensided shows that a great deal of slippage must have taken place.

This upward movement is believed to have initiated the anticline and to have determined its position. The extent of the plug along the strike may have been determined by the distribution of serpentine in the basement complex.

The upward movement was probably aided by the progressive erosion of the crest of the incipient anticline. The thorough fracturing and jumbling of the Franciscan rocks resulted from their being subjected to the stresses required for this movement. Whether the plug moved obliquely upward toward the southwest or vertically upward is debatable, but oblique movement is indicated by the attitude of the boundary fault, which in general dips from 35° to 90° outward except along the southwest edge, where it probably dips inward, and by the overturning of the strata on the southwest side of the plug. The many angular unconformities in the overlying sedimentary rocks, indicate that uplift and erosion in this

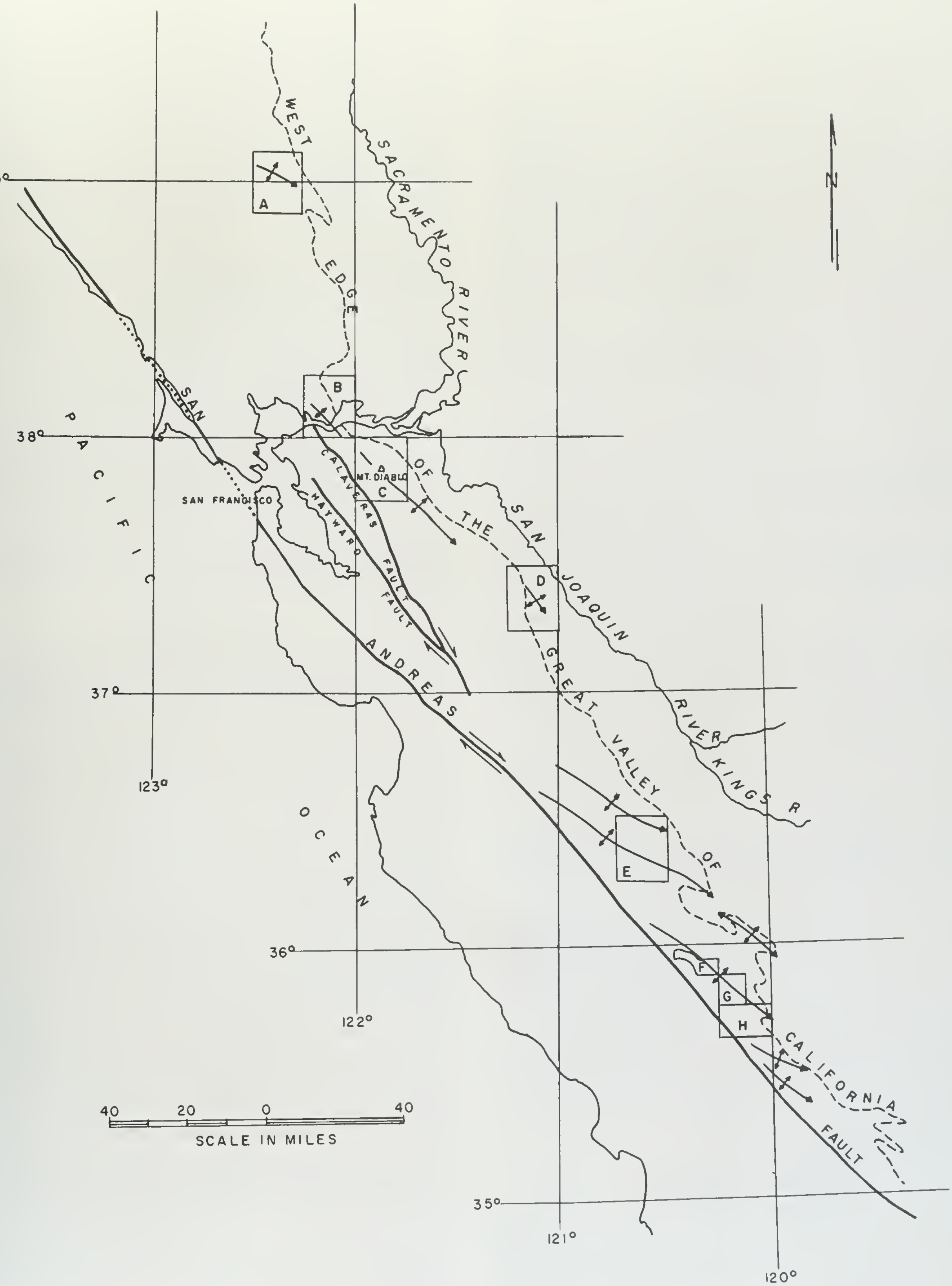

Figure 6. Index map showing some en echelon anticlines along the west side of the Great Valley of California and areas where piercement structures have been mapped. A, Wilbur Springs-Morgan Valley quadrangle; B, Carquinez quadrangle; C, Mount Diablo quadrangle; D, Mount Boardman quadrangle; E, New Idria quadrangle; F, Parkfield district; G, Tent Hills quadrangle; H, Orchard Peak area.

area occurred intermittently from Early Cretaceous to Recent time. The greatest movement appears to have occurred in post-Pliocene time, when the plug was permanently exposed to erosion.

Piercement structures similar to that of Mount Diablo have been recognized in the following places on the east edge of the Coast Ranges (fig. 6): in the Wilbur Springs quadrangle (Lawton, 1956); on Sulphur Springs Mountain (Weaver, 1949); in the Mount Boardman quadrangle (Maddock, 1955); in the New Idria area (Eckel and Myers, 1946); in the Parkfield district (Bailey, 1942); in the Tent Hills quadrangle (Herrera, 1950); and in the Orchard Peak area (Marsh, 1954). These structures, like the one in Mount Diablo, all consist of fault-bounded blocks of serpentine and Franciscan rocks, projecting through Upper Jurassic or Cretaceous strata along the crests of anticlines. The surface outlines of the upthrust blocks vary from sub-circular to eye-shaped, but the longest dimension of each is commonly parallel to the axis of the fold which it penetrates. The axes of these anticlines in general diverge only slightly from the San Andreas fault zone, whose relation to the folds is shown on figure 6, and the folds appear to have been formed by a component of compression in the San Andreas fault system. The location and shape of the plugs, as well as the location of the folds, was apparently determined by a structural pattern superimposed on the basement rocks by the ancestral San Andreas fault system before Late Jurassic time.

In the Coast Ranges the factors necessary to produce plugs of older rocks piercing the overlying beds are not fully known, but three of the requirements appear to be (1) lateral compression acting on (2) either relatively incompetent or mobile rocks or a system of fractures locally filled with mobile rocks (3) overlain by a thick pliable mantle of sedimentary rocks.

Plugs of older sedimentary rocks piercing younger strata that have undergone lateral compression have also been found in many of the salt-dome areas of the world. A classical example exists in the Carpathian region of Rumania, where according to Voitesti (*in* DeGolyer and others, 1926) Tertiary and older beds have been folded and faulted and hundreds of plugs composed chiefly of clay with minor amounts of salt have pierced the crests of the numerous parallel anticlines.

ECONOMIC GEOLOGY

The mineral commodities produced within the limits of the area shown on plate 1 have all come from the rocks of the basement complex. The metal that has been produced from this area in greatest amount is quicksilver, the total production of which, from 1875 to 1957, has exceeded 12,300 flasks, valued at more than $1,500,000. Other metals produced include copper and insignificant amounts of gold and silver. Numerous prospect holes expose traces of manganese minerals, and some chromite is said to have been mined from one prospect, but no production from it has been recorded.

In recent years metal mining has nearly ceased, but crushed stone quarrying has become an important industry, and the stone that has been produced has a greater total value than that of the metals previously mined. Production of crushed stone, which began in 1946, amounted to about $800,000 in 1957, raising the total value of stone produced to more than $2,500,000.

Small amounts of asbestos occur in the area but have no economic significance. Both fresh and brackish waters flow from springs on the mountain, and the brackish water is said to carry natural gas.

There is little published information about the mining activity in this area prior to 1930. Table 2 summarizes the rather sketchy information available and attempts to relate it to the prospects shown on plate 1. These and other mineral deposits in the surrounding area are described in a recent report on the mines and mineral resources of Contra Costa County by Davis and Goldman (1958).

Quicksilver

HISTORY AND PRODUCTION

The Mount Diablo quicksilver district extends along the northeast base of North Peak, in sections 28, 29, and 33, T. 1 N., R. 1 E. A man named Welch discovered cinnabar here, and located the first claim in 1863 or 1864, during the flurry of prospecting for copper, which began about 1862. Many other claims were afterward located in this area, including one placer claim where mercury and cinnabar were recovered by panning (Davis and Goldman, 1958, p. 531), but only the Ryne (Rhyne) mine, at the west end of the district, produced a notable amount of quicksilver. According to Irelan (1888, p. 162) this mine produced 85 flasks per month for a short period in the years from 1875 to 1877. Its total production is unknown but has been variously estimated at 300 to 1,000 flasks. The mine ceased operating in 1877, apparently because of litigation, and little is known of its history between that year and 1929, when it was leased by Mr. Vic Blomberg of the Mount Diablo Quicksilver Mines Company. The area east of the Ryne mine, containing the present Mount Diablo mine, had been prospected but only for the red sulfide, cinnabar. Some pits exposed showings of the black sulfide, metacinnabar, but apparently no attempt had been made to develop this material. In 1930-31 Mr. Blomberg and his partners produced 58 flasks of quicksilver by retorting ore taken from the Ryne mine area (figs. 7 and 8). At that time

Table 2. Mines and prospects in the Mount Diablo area.

Name (Number refers to plate 1)	Location		Commodity	Geology and workings	Production and history
	Section	Township, Range			
1. Harrison-Birdwell quarry	SE¼SW¼, 14	1N., 1W.	stone	Small cut exposing serpentinized diabase and clay gouge at intersection of two faults.	Small production of crushed stone in 1947 by Harrison-Birdwell Co. Abandoned because of geologic setting (Davis and Vernon, 1951, p. 586).
2. Pacific Cement and Aggregates quarry	NW¼, 23	1N., 1W.	stone	Hard unweathered diabase being quarried in open cut. Diabase contains a trace of disseminated pyrite. East edge of pit bounded by fault contact with shales of the Jurassic Knoxville formation.	Production of crushed stone begun in 1947 by Harrison-Birdwell Co. (Davis and Vernon, 1951, p. 586). Since 1954 operated by P.C.A. Plant capacity 2,400 tons per day.
3. Mount Zion Copper Co., mine	NW¼NW¼, 23	1N., 1W.	Cu,Au,Ag	Copper minerals, containing some gold and silver, in brecciated diabase. Two tunnels (inaccessible) followed the mineralized zone.	Mount Zion tunnel said to be about 1,100 feet long (M and SP 8:2:20, 1864*). Only a small amount of ore reportedly produced. Assay values of Au,Ag,Cu, equaled $4.75 per ton.
4. Silver mine (?)	NE¼NE¼, 22	1N., 1W.	Cu,Mn,Ag(?)	Shear zone 1 foot thick in diabase explored by tunnel about 50 feet long. Traces of copper and manganese minerals.	Possible small production during 1860's May be the "so-called silver mine" (Turner, 1891, p. 391).
5. Summit of Zion mine	NE¼NE¼, 22	1N., 1W.	Cu	Iron and copper oxides in sheared and altered diabase. Mineralized zone explored by vertical shaft about 120 feet deep and tunnel (inacessible) about 270 feet long.	Possible small production during 1860's (M and SP 8:2:20, 1864; 9:8:119, 1864; 10:12:182, 1865; 10:14:216, 1865*).
6. H. J. Kaiser quarry	NE¼, 22	1N., 1W.	stone	Hard unweathered diabase being quarried in benches. Diabase contains a little disseminated pyrite. Some pyrite-rich altered zones exposed in quarry face. Trace of fluorite (?) reported.	Production of crushed stone begun in 1955 after exploratory diamond drilling program. Plant capacity of 400 tons per hour.
7. Adit near Black Point	NW¼NE¼, 27	1N., 1W.	Cu	Chrysocolla and copper oxides in a network of carbonate veinlets in diabase. Mineralized shear zone explored by an adit bearing N. 80° W. for more than 50 feet, and a winze, dipping N., 30 feet from the portal. Trace of Hg in ore specimen.	Production of Cu from the (Mount Zion?) mine in 1902 and 1918 is less than 40,000 pounds (Davis and Vernon, 1951, p. 573).
8. Unity(?) claim	NW¼NW¼, 25	1N., 1W.	Ag	White quartz vein in brecciated diabase. Vein contains some chalcopyrite.	No production reported. Prospected for Ag (M and SP 10:12:182, 1865*).
9. La Feliz claim	SE¼NE¼, 26	1N., 1W.	Au-Ag	Vein in diabase reported to contain copper carbonates, sulfides, and vanadates plus calcite and quartz. Explored by more than 150 feet of underground workings.	Two tons of ore milled in San Francisco said to have assayed $26 per ton Au + Ag (M and SP 9:2:25, 1864; 10:12:182, 1865*).
10. San Pedro claim	SE¼NE¼, 26	1N., 1W.	Au-Ag	Copper and iron oxide minerals in brecciated diabase. Mineralized zone explored by 80 feet of drifts and crosscuts and a 22-foot winze.	Thirty tons of ore, 40 percent sulfides, mined in winze and milled at North Beach, San Francisco. Some assays of $40 to $45 per ton Au + Ag (M and SP 10:12:182, 1865*).
11. White Diamond claim	SW¼NW¼, 25	1N., 1W.	Au-Ag	Copper and iron oxides in vein in altered diabase explored by 10-foot adit bearing N. 70°W. Vein strikes N. dips 45°W. Ore specimen contains Fe, Cu, tr. Mn.	Prospected for gold and silver but not developed. Reported that 113 pounds of ore assayed $119 per ton Au + Ag (M and SP 10:12:182, 1865*).
12. Prospects in Mitchell Canyon	NE¼NW¼, 35	1N., 1W.	Cu	Chalcopyrite in shear zone 2 feet wide in diabase. Some chalcanthite on walls of prospect hole.	No production.
13, 14. Prospects near Arroyo del Cerro	E½, 33u	1N., 1W.	asbestos	Thin veinlets of cross-fiber chrysotile asbestos in sheared serpentine.	No production.
15. Prospects east of Russellman Park	SW¼SE¼, 19	1N., 1E.	asbestos	Thin veinlets of cross-fiber chrysotile asbestos in serpentinized pyroxenite.	No production.
16. Mount Diablo Rock and Aggregates pit	SW¼NW¼, 29	1N., 1E.	stone	Chert, greenstone, and graywacke of the Franciscan formation, mostly talus, excavated in open pit.	Intermittent production of crushed stone since 1954 reportedly about 65,000 tons.
17, 18. Prospects north of North Peak	NE¼SE¼, 30 NE¼SW¼, 29	1N., 1E.	Mn	Manganese oxides on fracture surfaces in chert of the Franciscan formation.	No production.
19. Bradley rock quarry	NW¼SE¼, 29	1N., 1E.	stone	Indurated graywacke of the Franciscan formation quarried in open cut.	Intermittent production of crushed and broken stone from 1946 to 1951 (Davis and Vernon, 1951, p. 576).
20. Ryne (Rhyne) mine	NW¼SE¼, 29	1N., 1E.	Hg	Cinnabar and a little metacinnabar disseminated through tabular body of silica-carbonate rock. Workings in 5 adits total more than 2,000 feet (pl. 4).	Oldest Hg mine in this district: original claims located by a Mr. Welch in 1863 or 1864 (M and SP 10:18:280, 1865*); first recorded production in 1875. Total production uncertain; estimated at 1,058 flasks.
21. Mount Diablo mine	NE¼SE¼, 29	1N., 1E.	Hg	Metacinnabar and less cinnabar on fractures and locally disseminated through silica-carbonate rock. Mineralized through a vertical range of at least 500 feet. Mined in open pit and underground workings (pl. 3, 5).	Discovery date uncertain. Overlooked by old timers who didn't recognize metacinnabar. Mined underground 1930 to 1946; open cut 1950 to 1951; explored underground 1955. Production from 1930 to 1957 more than 11,300 flasks.

Table 2. Mines and prospects in the Mount Diablo area.—Continued

Name (Number refers to plate 1)	Location: Section	Location: Township, Range	Commodity	Geology and workings	Production and history
22. Prospect near Sunshine Camp	SE¼SW¼, 28	1N., 1E.	Hg	Narrow sheared and argillized zone in rhyodacite explored by 35-foot incline. Iron oxides in sheared zone. Trace of Hg detected in iron oxides.	No production.
23. Prospect in Perkins Canyon	NW¼NW¼, 33	1N., 1E.	Hg	Rhyodacite plug intruded into Jurassic and Cretaceous shales. Breccia zone in rhyodacite cemented with calcite. Crystalline cinnabar, metacinnabar, and pyrite associated with the calcite. Mineralized zone explored by adit, now caved. Analysis of water issuing from the portal shown in table 4.	No production reported. Dump grown over and mostly washed away. Probably prospected in 1870's. Noted by Turner (1891, p. 392).
24. Prospect in Perkins Canyon	NW¼NW¼, 33	1N., 1E.	Hg	Narrow shear zone in rhyodacite explored by a 15-foot adit (caved). Traces of cinnabar and calcite.	No production.
25. Prospect in Perkins Canyon	NW¼NW¼, 33	1N., 1E.	Hg(?)	Massive brown and white mottled chert of the Franciscan formation explored by short adit (caved) bearing N. 47° W. No mineral seen.	No production.
26. Prospect in Perkins Canyon	NE¼SE¼, 32	1N., 1E.	asbestos	Cross-fiber asbestos veinlets in highly sheared serpentine. Fibers brittle and less than ¼ inch long. Explored by shaft (caved).	No production reported. Prospected by A. Drumeller in 1925. (Laizure, 1927, p. 7).
27. Prospect in Sycamore Canyon	SW¼SE¼, 32	1N., 1E.	asbestos	Cross-fiber asbestos veinlets in highly sheared serpentine. Fibers brittle and less than ¼ inch long.	No production reported. Prospected by A. Drumeller in 1925.
28. Prospect south of Sycamore Canyon	NW¼NW¼, 5	1S., 1E.	Cu,Zn(?), Hg(?)	Breccia zone 2 feet wide in micaceous graywacke and mica schist explored by 10-foot vertical shaft. Iron oxides in breccia zone contain Cu, tr. Zn, tr. Hg.	No production reported.
29. Prospect south of Sycamore Canyon	NW¼SW¼, 5	1S., 1E.	Mn	Manganese oxides in mica schist. Schist cut by veinlets of massive and crystalline quartz.	No production.
30. "Turtle Rock" quarry	SW¼SE¼, 2 u	1S., 1W.	dimension stone	Glaucophane schist quarried for use as building stone.	Small production probably totaling less than 20 tons; all used locally.

u = unsurveyed
* M and SP refer to Mining and Scientific Press, volume, number, and page follow.

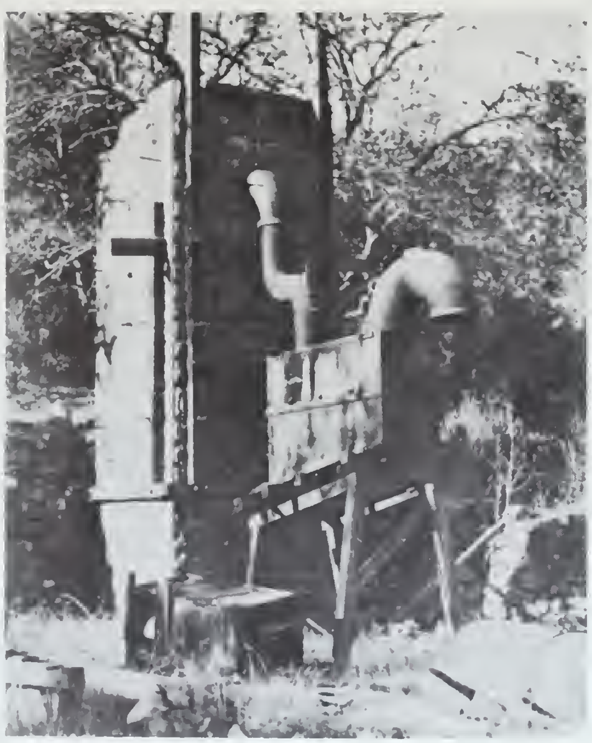

Figure 7. Retort and condensing chamber in which ore from the Ryne mine was treated, 1875-1877. (Photographs from Hofer and Staples, 1911.)

they also produced nine flasks of quicksilver by retorting metacinnabar taken from the original Adit level of the present Mount Diablo mine, and were thus the first to utilize metacinnabar in this district.

In 1933 the property known as the Mount Diablo mine was leased to C. W. Ericksen, who in a year and a half is said to have produced 730 flasks of quicksilver from an ore shoot opened up in a glory hole above the Adit level, a few hundred feet west-southwest of the present mill site (pl. 3). The ore in this shoot was quite rich in metacinnabar as well as cinnabar, and is said to have once yielded 48 flasks of quicksilver in 48 hours.

During 1934-35 Ericksen built the existing 40-ton Gould-type furnace plant, and in 1936 he sold the lease to the Bradley Mining Company. The Bradleys then laid out an underground mining program, together with a little surface work, to develop the ground adjacent to the glory hole. Ore taken from these workings yielded 10,455 flasks of quicksilver between 1937 and 1948, making the Mount Diablo quicksilver district rank ninth in U. S. production for the period 1940-1952, and twenty-ninth for total production during the period 1950-1952.

Quicksilver mining was interrupted in 1947, when the price of quicksilver dropped to less than $90 per flask. The Bradleys then installed rock crushers near the mill and began to produce crushed and broken stone from indurated graywacke of the Franciscan formation quarried near the Ryne mine (pl. 3).

In September 1951 the Mount Diablo mine was leased to R. B. Smith, who developed an open-pit operation over the underground workings near the mill. During the 55-day period from November 15, 1951, to January 17, 1952, this operation yielded 123 flasks of quicksilver. On the latter date, after prolonged rainstorms, landslides from the south face of the pit terminated operations on the productive benches.

Early in 1953 a D.M.E.A. (Defense Minerals Exploration Administration) exploration contract was awarded to Mr. Smith for exploring the Mount Diablo mine and some ground below its lowest level. A 330-foot shaft was sunk (pl. 3) and a crosscut was driven towards the old workings. The project was terminated in 1954 before completion. In 1955 the exploration project was completed by the Cordero Mining Company without D.M.E.A. assistance. Between the end of 1955 and June 1958, a few minor drilling and sampling projects were conducted in the open pit but no mining was done.

In June 1958 the Mount Diablo mine was leased by J. E. Johnson, who installed a washing and concentrating plant about 250 feet south of the furnace, to concentrate low-grade mineralized rock from the dumps and the open pit. In October 1958 a trial run of the plant yielded a concentrate containing 20 pounds of quicksilver per ton, but the operation was terminated shortly afterward because of Mr. Johnson's untimely death, without having produced any quicksilver.

According to mine records, 10,578 numbered flasks of quicksilver were shipped from the Mount Diablo mine between 1936 and 1952, and as noted above, unrecorded production from the Ryne mine was estimated as being

Figure 8. Seven-tube Johnson-McKoy retort used in Ryne mine area from 1930 to 1933. (Photograph by Vic Blomberg.)

Table 3. Production from the Mount Diablo quicksilver district, 1875-1957

	1875-1957				
Year	Ryne mine (flasks)	Mount Diablo mine (flasks)	Average value per flask	Approximate total value	Mount Diablo mine stone and calcines[1]
1875-1877	e1,000	--	e$54	$54,000	--
1930	58	9	e110	7,370	--
1933	--	730	54	39,420	--
1937	--	314	92	28,888	40
1938	--	1,361	73	99,353	6
1939	--	1,462	94	137,428	42
1940	--	1,084	175	189,700	263
1941	--	1,622	172	278,984	827
1942	--	1,366	191	260,906	375
1943	--	1,127	192	261,384	2,562
1944	--	698	109	76,082	1,886
1945	--	434	129	55,986	3,880
1946	--	861	97	83,517	11,253
1947	--	126	86	10,836	32,899
1948	--	--	--	--	25,739
1949	--	--	--	--	8,640
1950	--	--	--	--	9,356
1951-1952	--	123	205	25,215	--
1953-1957	--	--	--	--	--
Total	1,058	11,317	--	$1,564,069	$97,768

e = estimated

[1] In the quicksilver industry the waste products of the furnacing operation are called calcines; also called burnt ore.

between 300 to 1,000 flasks. The total production for the district, therefore, has probably exceeded 12,300 flasks (table 3).

GEOLOGIC SETTING

The two productive mines, the Mount Diablo and Ryne, are both in a lenticular body of silica-carbonate rock and serpentine that strikes northwest, dips 35°-70° northeast, and is about 2,000 feet long (pl. 3). This body lies in the boundary fault zone, which here separates graywacke of the Franciscan formation, with minor amounts of chert and shale, from well-bedded mudstone and sandstone of Cretaceous age. Quaternary landslides cover part of the area to depths ranging from a few inches to at least 35 feet. East and southeast of the mines, beyond the boundary fault zone, the Cretaceous rocks are cut by plugs of late Tertiary rhyodacite. A deposit of travertine covers a small area east of the Mount Diablo mine.

Silica-carbonate rock appears to extend from the east end of the Mount Diablo mine to the west end of the Ryne mine, though its continuity is obscured by landslides. Remnants of the serpentine from which this rock was derived crop out at each end of the silica-carbonate body and within it. Geologic maps of the underground workings also show inclusions of sheared sedimentary rocks in the silica-carbonate rock and serpentine, presumably incorporated during emplacement of the serpentine.

ORE DEPOSITS

Metacinnabar and cinnabar occur as fracture fillings and disseminations through the silica-carbonate rock and serpentine. Shaly beds and black clay gouge, similar to the "alta" * of other Coast Range quicksilver districts, apparently confined the ore-bearing solutions almost wholly to the fractured silica-carbonate rock and serpentine, for only small amounts of quicksilver were found in the adjacent sedimentary rocks. Cinnabar and metacinnabar also occur in fractures in the rhyodacite plug at the mouth of Perkins Canyon, indicating that the minerals were deposited in late Tertiary or early Quaternary time.

The ore in the Mount Diablo mine consists of metacinnabar and cinnabar in almost equal amounts, whereas that in the Ryne mine consists mainly of cinnabar with only a minor amount of metacinnabar. The gangue minerals in both mines are quartz, calcite, marcasite, and pyrite. In the Mount Diablo mine there were large bodies of massive iron sulfides, mostly marcasite, in brecciated silica-carbonate rock and silicified shale, and these were regarded as reliable indicators of ore. Specimens of ore from the Ryne mine, on the other hand, contain only small amounts of pyrite and marcasite. Stibnite occurs locally in the Mount Diablo mine, but not in sufficient quantity to interfere with furnacing. The iron sulfates copiapite and melanterite are common as oxidation products of the iron sulfides. The sulfates siderotil, epsomite, roemerite, and halotrichite were found by Ross (1940, p. 44) underground in the Mount Diablo mine. The greenish-yellow supergene mercury mineral schuetteite ($HgSO_4 \cdot 2HgO$), described by Bailey and others (1959), occurs around the old stack foundation a few hundred feet west of the D.M.E.A. shaft.

The gases methane, hydrogen sulfide, and sulfur dioxide are common underground in the Mount Diablo mine. They present no hazard, however, where modern ventilating techniques and electric lamps are used.

Study by the author of ore specimens from the open cut and the 300 level workings corroborated the following description of the mineralogy of the Mount Diablo mine by Ross (1940, p. 41-43):

"Most of the quicksilver sulphides appear to consist of intimate mixtures of cinnabar and metacinnabar, which form indistinctly banded, botyroidal masses. The cinnabar is the younger of the two sulphides. The dark metacinnabar masks the characteristically bright-red cinnabar, which, therefore, seems at first to be less abundant than it really is. * * * The two are seen in polished section to form an aggregate of twinned anisotropic grains that in places seem to intergrade into each other. The grains of faintly bluish metacinnabar, in part rounded by corrosion, seem to float in the cream-colored cinnabar. In most of the material the red color of the cinnabar is not visible in the polished section except along scratches and cracks * * *. Some of the more coarsely granular aggregates of cinnabar, however, show brilliant red by internal reflection without being scratched. * * *

"Both marcasite and pyrite are commonly present and locally abundant. Much of the pyrite constitutes residual grains, in part intricately embayed, that are embedded in the quicksilver minerals, but well-formed untarnished pyrite cubes stud the walls of some vugs. Marcasite is the more abundant of the two iron sulphides. Most of it is enclosed in and partly embayed by the quicksilver minerals and must, therefore, have crystallized earlier than these; but much of it forms uncorroded crystals. Much of the marcasite in the larger openings between sandstone fragments is in crustified bands, and where the openings are not completely filled they are commonly lined by the crystal-studded surfaces of such bands. Marcasite also forms filaments that ramify through the sandstone. Most such material fills tiny cracks, but here and there marcasite crystals enclosed in unbroken sandstone were presumably formed by replacement. Stringers, filaments, and scattered grains of the iron sulphides, mainly marcasite, are widely distributed in small quantities in the sedimentary rocks throughout the mine.

Stibnite-bearing quartz veins cut the mineralized rock, representing the most recent stage in the deposition of metallic minerals.

Ryne mine

The Ryne mine (20 on pl. 1) is at the west end of the Mount Diablo quicksilver district, where the lens of serpentine and silica-carbonate is relatively thin and encloses other lenses of Franciscan rocks (section B-B′, pl. 3). The underground workings have a total length of

* Spanish for "high", "elevated", "above". A term coined by Mexican miners at New Almaden for the black clay gouge which invariably capped or overlay the quicksilver ore shoots.

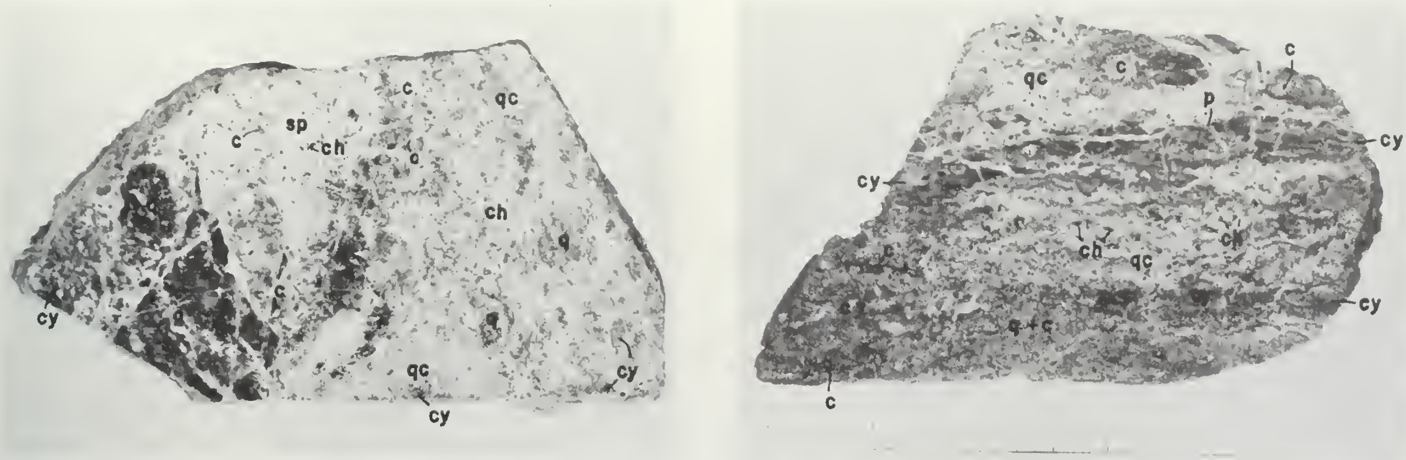

Figure 9. Polished specimens of silica-carbonate rock from the Ryne mine. Crystalline quartz (q) is black, chalcedony (cy) is dark-gray, quartz and carbonate mixture (qc) is mottled gray, partially altered serpentine (sp) is white, chromite (ch) is black, and pyrite (p) is light-gray; cinnabar (c), disseminated throughout the specimens, is medium-gray. (Bar scale is two inches long.)

more than 2,000 feet, but are now mostly inaccessible (see pl. 4). Unfortunately there is no map of the old Ryne adit, so that only its approximate position and extent are shown. The principal ore shoots apparently extended along west-trending north-dipping fissures exposed in the Ryne, Jones, and Camp workings, and according to the mine maps cinnabar was found in fractures in Franciscan sedimentary rocks as well as in the silica-carbonate rocks. Mr. Blomberg, who saw all the underground workings, says that the stopes were small, so that the ore must have been very rich to account for the production rate of 85 flasks per month reported by Irelan (1888, p. 162).

Specimens of ore from these workings contain crystalline aggregates of cinnabar and a little metacinnabar disseminated through silica-carbonate rock. Pyrite, which occurs in small amount, appears to be the principal iron sulfide, though some marcasite was noted (fig. 9).

Mount Diablo mine

The Mount Diablo mine (21 on pl. 1), commonly referred to as the Mill Workings, is about half a mile east of the Ryne mine area. Landslides cover the bedrock between the two mines, but the tabular body of serpentine and silica-carbonate rock is probably continuous between them.

Plate 5 shows the extent of the underground workings prior to the open-cut operation which removed most of the Adit level. Underground workings, including the Adit level, all inaccessible in 1957, totaled about 4,570 feet on five levels having a vertical range of 300 feet. Quicksilver ore was found through a vertical range of about 500 feet, from the 360 level to the highest outcrop.

In this area the mineralized zone is up to 160 feet thick, and here as in the Ryne mine area it encloses lenses or septa of Franciscan rocks and serpentine. The best ore was in fractured and brecciated silica-carbonate rock along the footwall of the mineralized zone (section A-A′, pl. 3), and was commonly associated with pods of massive iron sulfides. Two tabular ore shoots were mined; one of them, mined in the E stopes between the 80 and 165 levels, plunged steeply northeast, and the other, mined in the W stopes between the Adit and 165 levels, plunged about 50° north (pl. 5). The northeast-plunging shoot averaged 80 feet along the strike, 120 feet down the dip, and 6 feet thick. The north-plunging shoot averaged 130 feet along the strike, 200 feet down the dip, and 6 feet thick. Ore mined from these shoots from 1936 to 1947 averaged about 10 pounds of quicksilver per ton. During the same period reserves of low-grade ore were blocked out below the 165 level in the W slopes along the Main winze. Recent work on the 360 level exposed some low-grade ore (3 to 10 pounds of quicksilver per ton) near the Main winze; exploration on this level under the northeast-plunging shoot uncovered only traces of metacinnabar and cinnabar.

Part of the ore zone above the 80 level is exposed in the open cut at the west ends of benches 5 and 6. Here the silica-carbonate rock is cut by numerous open fractures that strike north to northwest. Dodecahedral crystals of metacinnabar, partly covered with a thin botryoidal coating of marcasite, line these fracture surfaces (fig. 10), and crystalline masses of metacinnabar weighing as much as half a pound occur in some places where the fractures are completely filled. As noted above, cinnabar occurs with the metacinnabar, but its red color is commonly masked by the black sulfide. On close examination the metacinnabar crystals are seen to be partially converted to cinnabar. Marcasite nodules up to three inches in diameter are common in the bands of black clay gouge which cut the silica-carbonate rock on bench number 6.

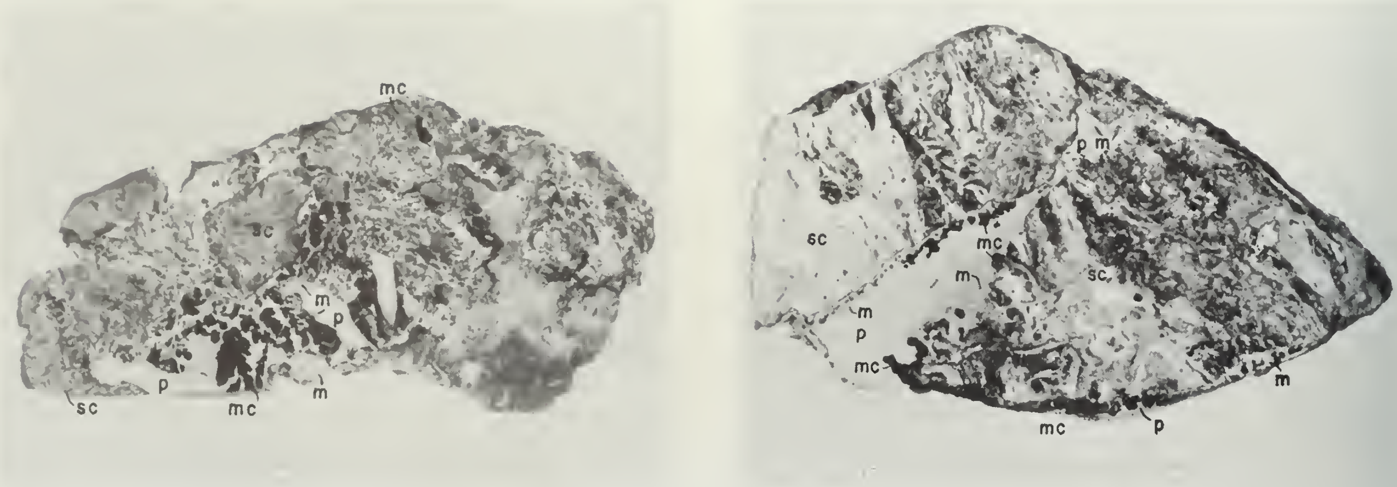

Figure 10. Polished ore specimens from the Mount Diablo mine open cut, showing ore and gangue minerals filling fractures in silica-carbonate rock. Silica-carbonate rock (sc) is black and white; metacinnabar (mc) is black, pyrite (p) is light gray, and marcasite (m) is dark gray. (Bar scale is two inches long.)

The quicksilver ore now exposed in the open cut seems to be concentrated in a zone under the hanging-wall fault, along the north side of bench number 6. Whether this same zone is mineralized at depth is not yet known.

Section A-A′ (pl. 3) shows that the dip of the footwall flattens slightly between the 80 and 165 levels. This local flattening may have been one of the principal structural controls of this deposit, for much of the good ore was between these levels, and little ore was found between the 165 and 360 levels, where the footwall is steeper. Below the 360 level the footwall doubtless flattens again, but the vertical depth to the next favorable zone cannot be accurately predicted. Alternate steepening and flattening of serpentine contacts, with ore shoots localized under the flat areas, is common in some California Coast Range quicksilver deposits, as for example in the Abbott mine in Lake County.

Prospects in Perkins Canyon

At the mouth of Perkins Canyon, half a mile south of the Mount Diablo mine, two prospect adits have been driven on showings of cinnabar in an intrusive body of rhyodacite. The north adit (23 on pl. 1) is caved, but specimens containing cinnabar, metacinnabar, and pyrite in calcite veinlets in rhyodacite were found on its dump. This is the quicksilver prospect where Turner (1891, p. 392) noted that "solfataric action is still going on." The south adit (24 on pl. 1), only a few feet from the first, is about 15 feet long and follows a shear zone in rhyodacite. Some cinnabar and pyrite on calcite were also seen here.

A few hundred feet west of these adits is a third (25 on pl. 1), now completely caved, which was driven in rocks of the Franciscan formation. It showed no metallic minerals.

The cinnabar-bearing iron-stained quartz vein noted by Turner (1891, p. 392) about one mile south of the main peak was not found during this study.

Prospect near Sunshine Camp

On the south side of the rhyodacite plug near Sunshine Camp (22 on pl. 1) a 35-foot tunnel follows a narrow shear zone that strikes N. 35° E. and dips 35° NW. The rhyodacite adjacent to this shear zone has undergone mild hydrothermal alteration, which has changed much of the feldspar to kaolinite and quartz. A sample of iron oxides occurring with the altered rhyodacite in the shear zone was found, when tested with an ultra-violet light and willemite screen, to contain traces of mercury, and chemical tests showed 53 parts per million of mercury, although the sample contained no visible quicksilver minerals or other sulfides.

ORIGIN

In this district, as in many other Coast Range quicksilver districts, the ore deposits are mostly in silica-carbonate rock that was formed by the hydrothermal alteration of serpentine in late Tertiary time. The rock was then fractured and brecciated by continuing deformation and unlift of the Mount Diablo plug, some rhyodacite was intruded, and ore-bearing solutions deposited sulfides of mercury and iron in the silica-carbonate rock and rhyodacite.

Becker (1888, p. 379) and Ross (1940, p. 50) both found clues to the origin of the quicksilver deposits in the association of quicksilver minerals with volcanic rocks, hot-spring deposits (travertine), and methane and sulfurous (H_2S?) gases. They believed that the andesitic or related igneous magma was the source of thermal solutions which transported and deposited the quicksilver minerals, and they regarded the continuing escape of gases as evidence that the ore was deposited somewhat recently. I found no reason for doubting these conclusions.

The chemical composition of the ore-bearing solutions is so little known that it is uncertain whether they were acid or alkaline. It is evident, however, that much of the ore in the Mount Diablo mine was first precipitated as metacinnabar and then partially converted to the more stable form, cinnabar, whereas in the Ryne mine area cinnabar was deposited directly from the solutions. The geochemical aspects of the ore-bearing solutions and of the relation between metacinnabar and cinnabar have been discussed by others. Dreyer (1940) says that cinnabar can precipitate only in an alkaline sulfide solution, and that acidification of the solution will cause it to precipitate metacinnabar and not cinnabar. Krauskopf's (1951) thermodynamic calculations show that slightly alkaline solutions of sodium sulfide can carry enough HgS to act as ore carriers. Dickson and Tunell (1955) say that the association of metacinnabar and cinnabar deposited from sodium sulfide solutions is probably the result of fluctuating temperature or changing chemical conditions or a combination of these things, and that the occurrence of two forms of mercury sulfide in this district could have been caused by falling temperature or by contamination of the ore-bearing solutions.

A sample of travertine from the Mount Diablo mine contained 7 ppm of mercury. The source of this mercury is not known, and it may have been deposited very recently from mine waters flowing over the travertine. It is also possible, however, that the mercury was precipitated from the same waters that deposited the travertine and that these or similar waters carried the ore in this district.

OUTLOOK

Indicated and inferred reserves of low-grade ore (3 to 10 lb. Hg/ton) still exist in the Mount Diablo mine, and inferred reserves in the Ryne mine. The Mount Diablo mine offers the better possibilities of yielding high-grade ore, because more is known of its geology and structure. Favorable places for underground exploration in this mine are (1) the mineralized zone under the hanging-wall fault, now exposed in the open pit, (2) southeast and northwest of the workings on the 360 level along the footwall ore zone, and (3) down dip below the 360 level where the footwall structure probably flattens again. Underground exploration in the Ryne mine would probably reveal some low-grade ore, but no specific areas can be recommended.

Perhaps the best place for exploratory work lies under the landslide cover between the two mines. If the mineralized rock is continuous between these deposits, there is a good chance of its containing minable ore shoots.

Copper

Mining in the Clayton district, on and near Mount Zion and Eagle Peak, began about 1860 with the discovery of copper minerals in veins cutting the diabase. A copper rush took place during the years 1862 to 1864, and Cronise (1868, p. 161) reports that some 50 copper deposits were prospected. Small scale copper mining is said to have been done in 1908 (Laizure, 1927, p. 15) and 1918 (Davis and Vernon, 1951, p. 573); the total recorded production, however, amounted to only 40,000 pounds of copper. Some of the properties named in old reports are the Mount Zion, Keokuk, Great Republic, Superior, Pioneer, Unexpected, Summit of Zion, Horse Shoe, Hall, Last Chance, Nucleus, Reconstruction, Tecumseh, Wahhooken, and Alpine, but the locations of most of them are unknown. An old copper smelter constructed in Mitchell Canyon during the rush (figured by Purcell, 1940, p. 641) has since been removed or destroyed, and stone quarrying operations are slowly obliterating the workings of the Mount Zion and Summit of Zion mines.

The copper minerals are chiefly confined to the diabase north of the serpentine band, but a veinlet containing oxidized copper minerals cuts a schist body south of the Mount Diablo mine. Chalcopyrite, pyrite, oxides of copper and iron, and traces of chrysocolla and malachite found on the old dumps probably represent the ore minerals. They commonly occur either in quartz forming veins in diabase or cementing brecciated diabase, or as grains disseminated in zones of altered diabase. Some chalcanthite was noted in one prospect, and some of the copper ore is said to have contained native copper and fluorite (Hanks, 1884, p. 181). Gold and silver are said to have been present in the copper ores, but neither was detected in specimens collected during the present study.

Two samples of copper ore, when tested with the ultra-violet lamp and willemite screen, were found to contain traces of mercury. One of these, which came from the adit near Black Point (7 on pl. 1), consisted of chrysocolla, malachite, hematite, and limonite, and contained 21 ppm of mercury. The other, from a prospect (28 on pl. 1) in the NW¼ sec. 5, T. 1 S., R. 1 E. contained oxides of copper, zinc (?), and iron and 13 ppm of mercury. The form in which mercury occurs in the copper ore is not known, but its presence indicates a possible genetic relationship between copper and mercury. It is possible that these two elements are combined in the mineral schwazite, as they are in the quicksilver deposits of southeastern Oregon described by Williams and Compton (1953).

The copper mines in the Clayton district appear unlikely to become productive.

Gold and Silver

During the copper rush of 1862-1864 the copper ores were reported to contain gold. Melville (*in* Turner, 1891, p. 391) found gold associated with chalcopyrite and bornite, and other writers describe gold values of $4 to $48 per ton.

Silver also was said to occur in the copper ores on Mount Zion, and Turner (1891, p. 391) refers to a "so-called silver mine in the northern slope of Pyramid Hill (Mount Zion)" (4 on pl. 1). Cronise (1868, p. 161) reports that 60 pounds of ore from the Open Sesame claim yielded $48 in gold per ton and $243 in silver per ton, and that some ore from the San Pedro ledge yielded $40 in silver per ton. Other assays, however, made on larger lots of ore, averaged less than $5 per ton in silver and gold together. Prospecting for silver near Clayton was noted by Irelan (1888, p. 162), but he gave no specific details regarding its results.

The most promising gold and silver prospects are said to have been in the Back Canyon area south of Clayton. The names of some of the claims in this area were White Diamond, La Feliz, Unity, Carmel, and Santa Domingo. Although some gold and silver were probably obtained from the ores mined in this area no production has been recorded.

Chromite

A note by Laizure (1927, p. 12) mentions the Mount Zion chrome mine in T. 1 N., R. 1 W., but no workings were detected here. Chromite occurs as an accessory mineral in the serpentine but not as ore.

Manganese

Bradley and others (1918, p. 32) reported small bunches of manganese ore on the southeast side of Mount Diablo (29 on pl. 1). I noted manganese stains on fractures in chert in many places south of the serpentine dike, but saw no ore. Less than one percent of manganese was found in an ore specimen from the "silver mine" (4 on pl. 1). No development work has been done on any of the showings.

Asbestos

In 1925 A. Drumeller located claims for asbestos in Perkins Canyon. A shaft, now caved, was sunk in a small serpentine lens in the E½ section 32 (26 on pl. 1), and prospect pits were dug in the serpentine body in the S½ section 32 (27 on pl. 1). Other prospect holes (13, 14, 15 on pl. 1) in serpentine were noted but none had been developed. Crossfiber chrysotile with fibers as much as ¼-inch long is common in all the serpentine masses but no material of commercial quantity was observed.

Crushed and Broken Stone

Crushed and broken stone has been produced from four open-cut operations along the north edge of the mapped area since 1946, but only the two largest quarries were being worked in 1957. Total production from them through 1957 amounts to more than 2,000,000 tons, valued at more than $2,500,000. Diabase, indurated graywacke, and talus containing chert, greenstone and graywacke of the Franciscan formation, have been or are being quarried, and the reserves of raw material are large. The four localities are described below.

BRADLEY MINING COMPANY

A quarry (19 on pl. 1) in massive indurated graywacke of the Franciscan formation was opened in section 29, near the Ryne mine, in 1946. Davis and Vernon (1951, p. 576) report that this quarry was operated full time for less than a year after being opened, but it was worked intermittently until 1951. The total production of stone from the quarry is not known, but it constitutes a large percentage of the combined rock and calcines listed in table 3.

H. J. KAISER COMPANY

In 1955, the H. J. Kaiser Company began production of crushed stone for use as road base material from fine- to medium-grained diabase in a quarry (6 on pl. 1) in the NE¼ section 22, on the west slope of Mount Zion.

Prior to the opening of this quarry the proposed site was explored by sinking eight diamond-drill holes, ranging in depth from about 100 to 500 feet. A heavy overburden of weathered diabase, up to 25 feet thick, necessitated extensive stripping before actual quarrying began. In 1957 the plant had a capacity of 400 tons per hour.

Cores recovered from the diamond-drill holes are reported to indicate that the holes cut zones of hydrothermally altered diabase as much as 10 feet thick containing several layers of iron sulfides 3 to 4 inches thick. These and the narrow altered zones, containing 20 to 30 percent of disseminated pyrite and chalcopyrite, which are occasionally exposed in the quarry face are probably similar to those prospected during the copper rush of the 1860's. A purple crystalline mineral, probably fluorite, is said to be found in vugs in the fresh diabase (see p. 58). The diabase is selectively quarried to obtain only the fresh rock.

MOUNT DIABLO ROCK AND AGGREGATES COMPANY

The Mount Diablo Rock and Aggregates Company began producing crushed stone in 1954 from a pit (16 on pl. 1) in the NW¼ section 29, half a mile west of the Ryne mine. The company produced about 65,000 tons in 1954, but has operated only intermittently since that time. The material produced in this operation is taken from talus consisting of chert, greenstone, and graywacke of the Franciscan formation.

PACIFIC CEMENT AND AGGREGATES INCORPORATED

In 1947 two stone quarries were opened by the Harrison-Birdwell Company on the east slope of Mount Zion, a small one (1 on pl. 1) in the SW¼ section 14 and a large one (2 on pl. 1) in section 23. The small one was opened first, but was abandoned in the same year owing to an unfavorable geologic setting; it was at the intersection of two faults and exposed sheared and serpentinized diabase and clay gouge. The quarry in section 23 was then opened in fine- to medium-grained diabase. In 1954 the Pacific Cement and Aggregates Company leased the property as a source of crushed stone for road base materials and began to expand quarry and plant facilities. In 1957 the plant had a capacity of 2,400 tons per day. As in the Kaiser quarry, a large amount of overburden must be removed before fresh diabase is reached.

Dimension Stone

Glaucophane schist has been used as building stone in and around the State Park. The outcrop of schist (30 on pl. 1) near Turtle Rock has supplied the stone used in the park buildings and in those on the Turtle Rock Ranch. The total schist outcrop, however, is too small and inaccessible for anything but a very small quarrying operation.

The rock is broken into irregular pieces with one flat side. Its dusky blue color makes it look very handsome when laid in walls and fireplaces.

Limestone

No economic deposits of limestone occur within the area shown on plate 1, but large deposits of calcium carbonate in the form of travertine occur two miles west of Mount Zion on Lime Ridge. Logan (1947, p. 220) says that some of this travertine was mined and burned as early as 1851, and that the deposits were worked intermittently until 1946. The Henry Cowell Lime Company was the principal user of the travertine, which it used in making portland cement in its plant at Cowell. Small amounts were also used by the Spreckels Sugar Company and the Selby smelter.

The travertine deposit at the Mount Diablo mine is too small to be of economic importance.

Ground Water

On and around Mount Diablo there are springs and wells yielding various kinds of water—fresh, saline, and sulfurous. Most of the springs are seasonal and yield little water during the summer months, but there are many exceptions.

Of the numerous fresh-water springs on Mount Diablo, those that appear to give the largest and most constant flow are within serpentine bodies and along their edges. The most copious flow observed comes from a spring in Russellman Park on the north side of North Peak, which yields a constant flow of water from a 6-inch pipe all year. West of the Ryne mine, along the north base of North Peak, springs in serpentine yield a small but constant flow of water, and springs near the head of Mitchell Canyon, also in serpentine, supply sufficient water during the summer for recreational facilities at the mouth of the canyon. A small but constant flow of water from springs in sheared Franciscan rocks, on the south slope of the mountain, supplies the State Park facilities on Mount Diablo. Peach Tree Springs and most of the other springs on the mountain are either on the boundary fault zone or in shear zones within the area of broken Franciscan rocks.

Saline or brackish-water springs issue in some places around the base of Mount Diablo, near the boundary fault. One of these is in the SW¼SW¼ section 15, about a mile northwest of Mount Zion, and there are said to be others near the P.C.A. quarry in the SW¼ section 14, near the Mount Diablo mine in the SW¼ section 28, and farther southeast. A water well 500 feet deep in the SW¼NE¼ section 15 yields brackish water and considerable natural gas. These waters (table 4), according to White (1957; 1960), have the following features which when considered together are characteristically associated with connate waters of the Na-Ca-Cl type: Ca/Na ratio greater than 0.1; high Cl, NH_4, I/Cl, and total parts per million of soluble material; low K/Na and Li/Na; and very low SO_4. Some dilution of the connate water, probably by meteoric water, however, is indicated by the fact that the ratios of the soluble components agree systematically with those of oilfield brines (White, 1957, table 4; 1960, p. 453) even though the total parts per million of soluble material here is less than in the brines. The amounts of boron, halogens, and bicarbonate in sample 3 are relatively high, but they are within the limits determined for connate waters; perhaps this water has been diluted by some metamorphic water, which is typically high in boron, bicarbonate and sodium (White, 1960, p. 453).

There are two flowing sulfur springs in this area, one in Pine Canyon about 4 miles due west of the main peak, and one at the mouth of Perkins Canyon in the NW¼-NW¼ section 33. The spring in Pine Canyon was reported by Waring (1915, p. 270) to be "moderately sulphuretted with a temperature of 67° F." The spring in Perkins Canyon, which has a very small flow, gives off a mild odor of hydrogen sulfide. It is in an old quicksilver prospect adit (23 on pl. 1) driven along a fault in rhyodacite. Turner (1891, p. 391) reported a sulfur spring near the old Ryne mine, but this spring ceased flowing in 1956.

Table 4. Analyses of some waters from the Mount Diablo area (in parts per million).

(Analyst C. E. Roberson, U.S. Geological Survey)

	1	2	3
Temp. °C	23	23	21
pH	9.1	9.5	7.7
SiO_2	23	17	16
Fe	.32	.18	.34
Al	.10	.18	1.3
Mn	.02	.03	.13
Cu	.02	.02	.00
Pb	.00	.00	.00
Zn	.00	.00	.0
Ca	286	679	431
Mg	.0	.0	31
Na	1500	2410	3100
Ba	2.1	1.6	23
K	7.6	12	53
Li	.0	.0	4.6
B	10	7.4	191
NH_4	13	21	57
As	.00	.00	.00
OH	9.2	45	
CO_3	64	42	0
HCO_3			203
SO_4	16	6.6	1.6
Cl	2750	4870	5770
F	.20	.05	2.5
Br	8.0	16	14
I	7.5	14	15
NO_3	2.2	3.7	.0
NO_2	.0	.0	.0
PO_4	.15	.00	.00
H_2S	.5	1.9	.4
Sum	4709.01	8157.16	9922.57
Ratios by wt.			
HCO_3/Cl[1]	.046	.017	.035
SO_4/Cl	.0058	.014	.00028
F/Cl	.00007	.00001	.00043
Br/Cl	.0029	.0032	.0024
I/Cl	.0027	.0029	.0026
B/Cl	.0036	.0015	.033
Ca/Na	.19	.28	.14
K/Na	.005	.005	.017
Li/Na			.0015
Ca+Mg/Na+K	.19	.28	.15

1. Spring in the SW¼ sec. 15, T. 1 N., R. 1 W., MDBM; reported to give off methane.
2. Water well 500 ft. deep in the NE¼ sec. 15, T. 1 N., R. 1 W., MDBM; gives off methane.
3. Sulfur spring in Perkins Canyon, NW¼ sec. 33, T. 1 N., R. 1 E., MDBM; in old quicksilver prospect in rhyodacite.

[1] Includes CO_3 as equivalent HCO_3.

The spring that deposited the travertine down-slope from the Mount Diablo mine is now covered with waste from the open pit, but old mine maps indicate that it was near the portal of the 165-level drainage adit. In 1957 some water still issued from the waste but its source was uncertain.

Natural Gas

Natural gas (marsh gas, or methane) is reported from three localities along the periphery of the Mount Diablo plug. One is the underground workings of the Mount Diablo mine, and the other two are a water well and a spring northwest of Mount Zion. Only a small volume of gas issues from the mine, but it is sufficient to prohibit the use of lamps with an open flame. The water well drilled by the H. J. Kaiser Company in the NE¼ section 15 yields an appreciable quantity of methane: gas pressures up to 35 psi were reported in 1956 while the well was temporarily capped. A brackish spring in the SW¼ section 15 is also said to give off methane, and its water is covered with an oily scum.

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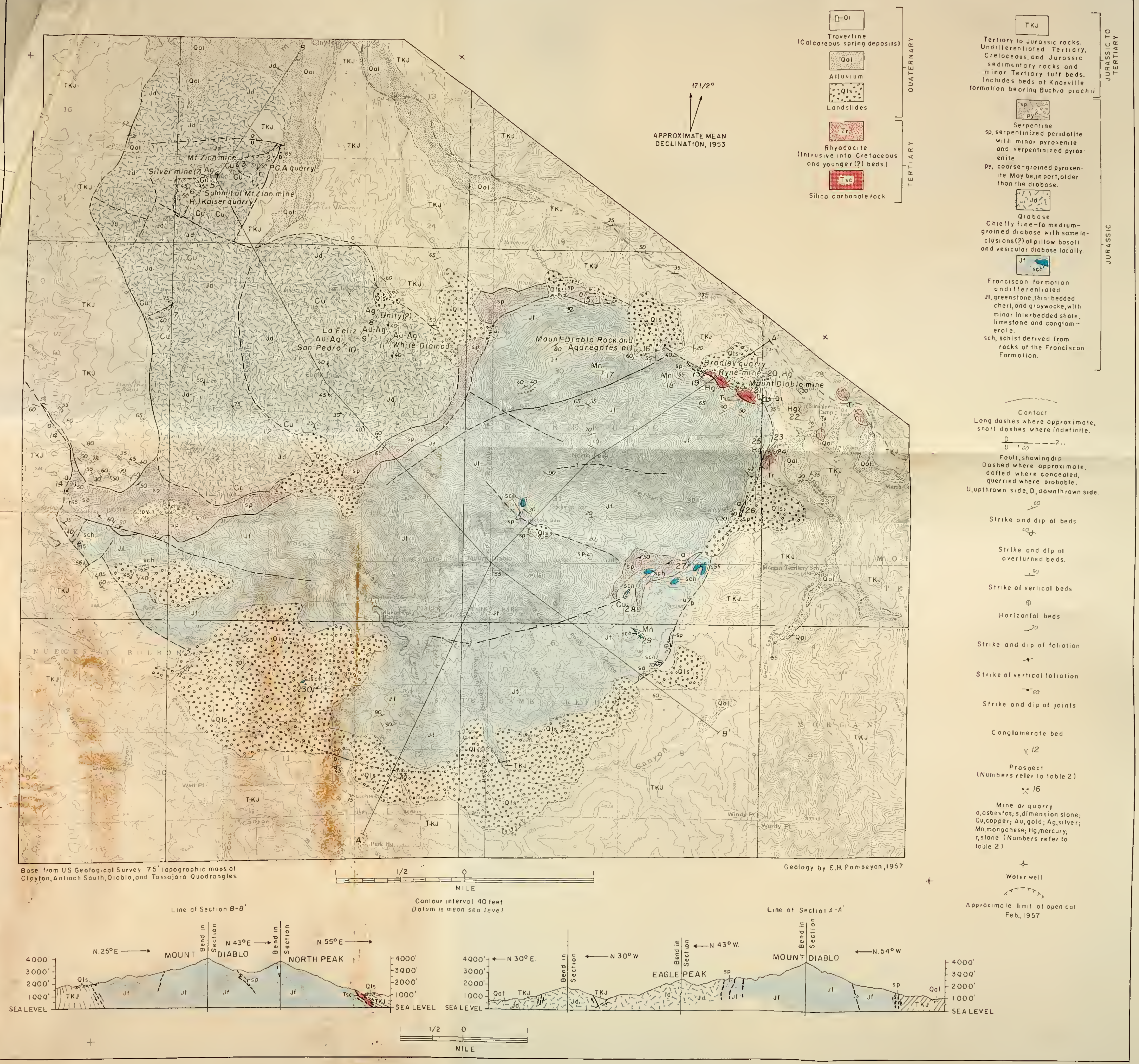
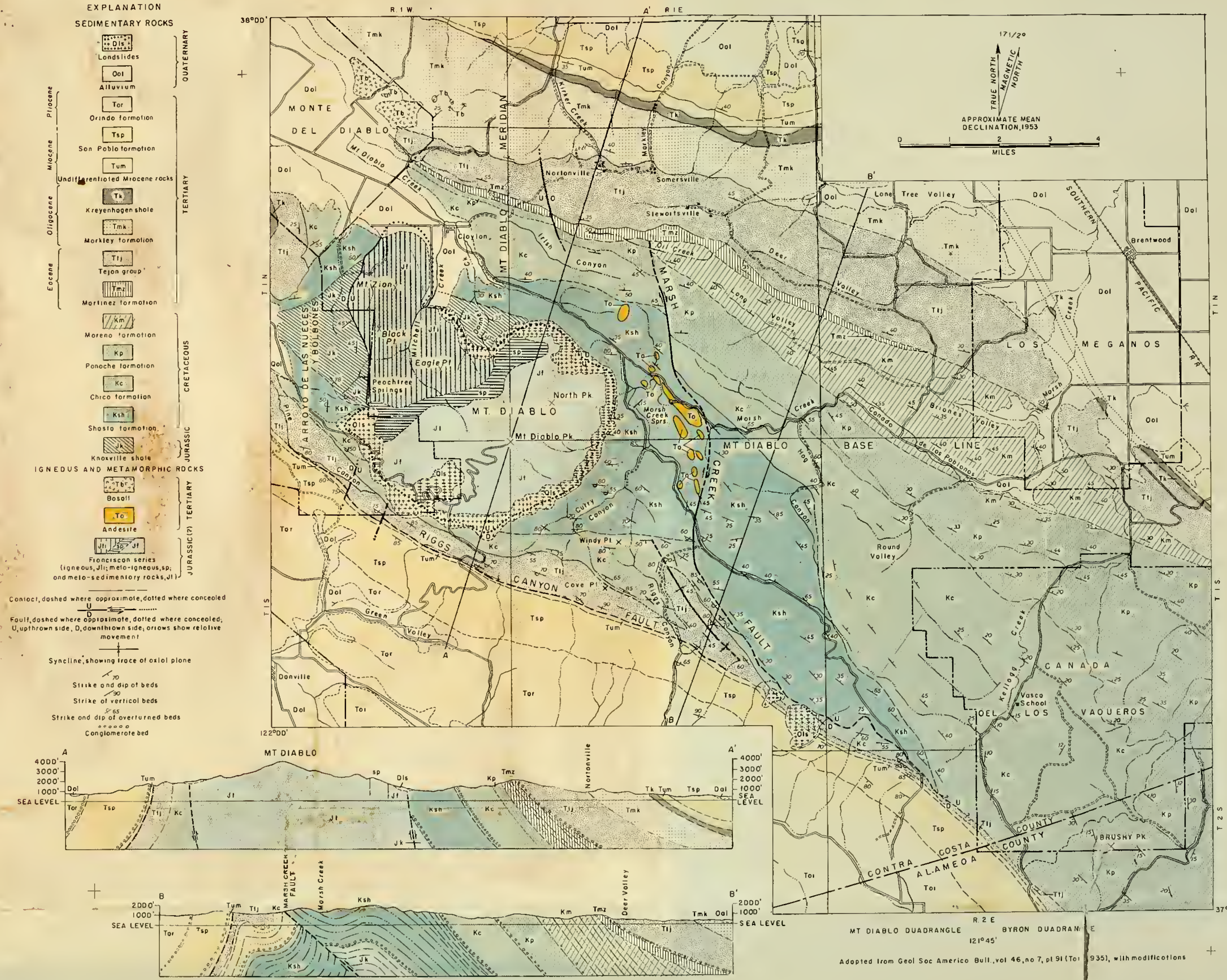
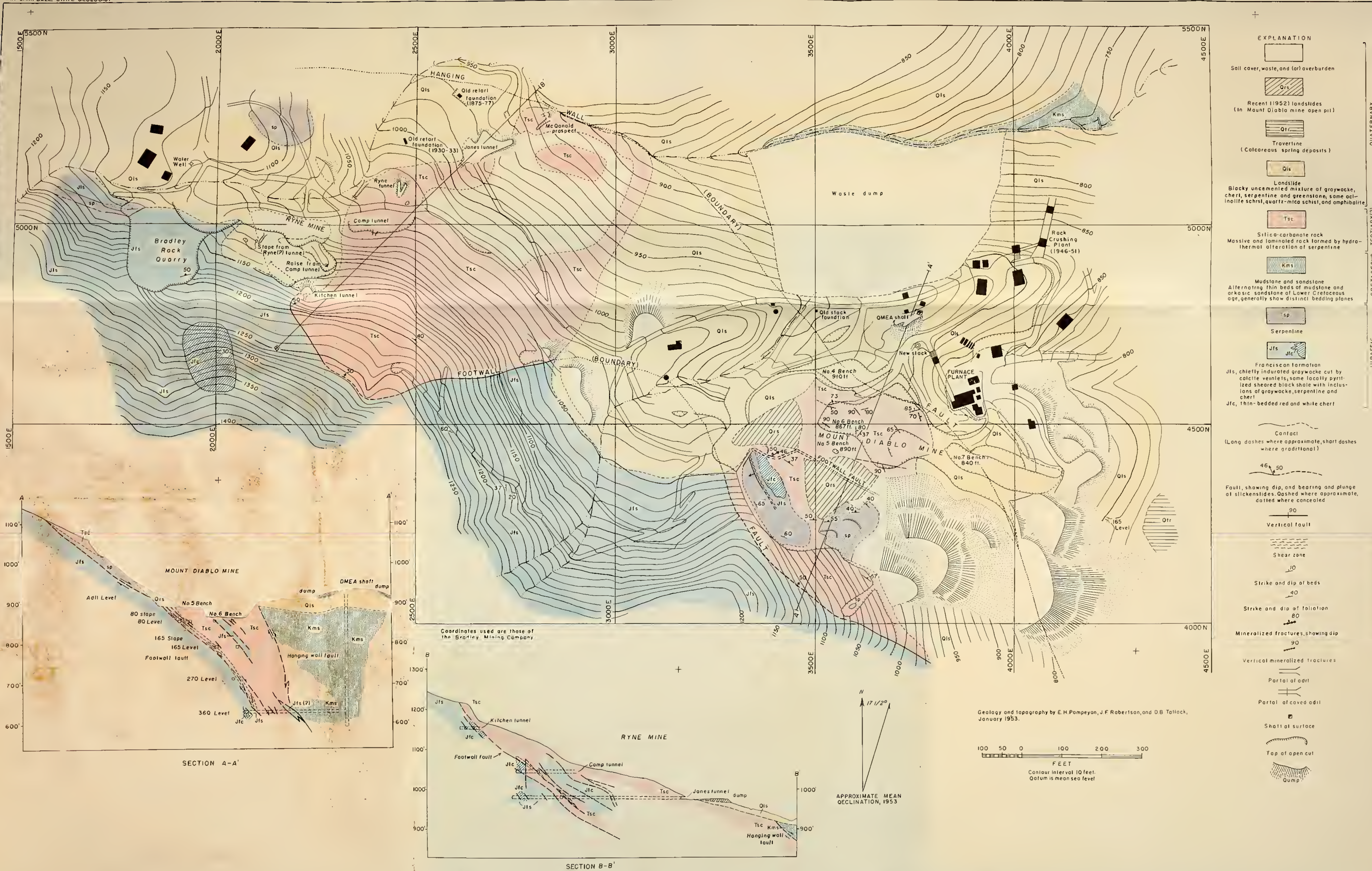


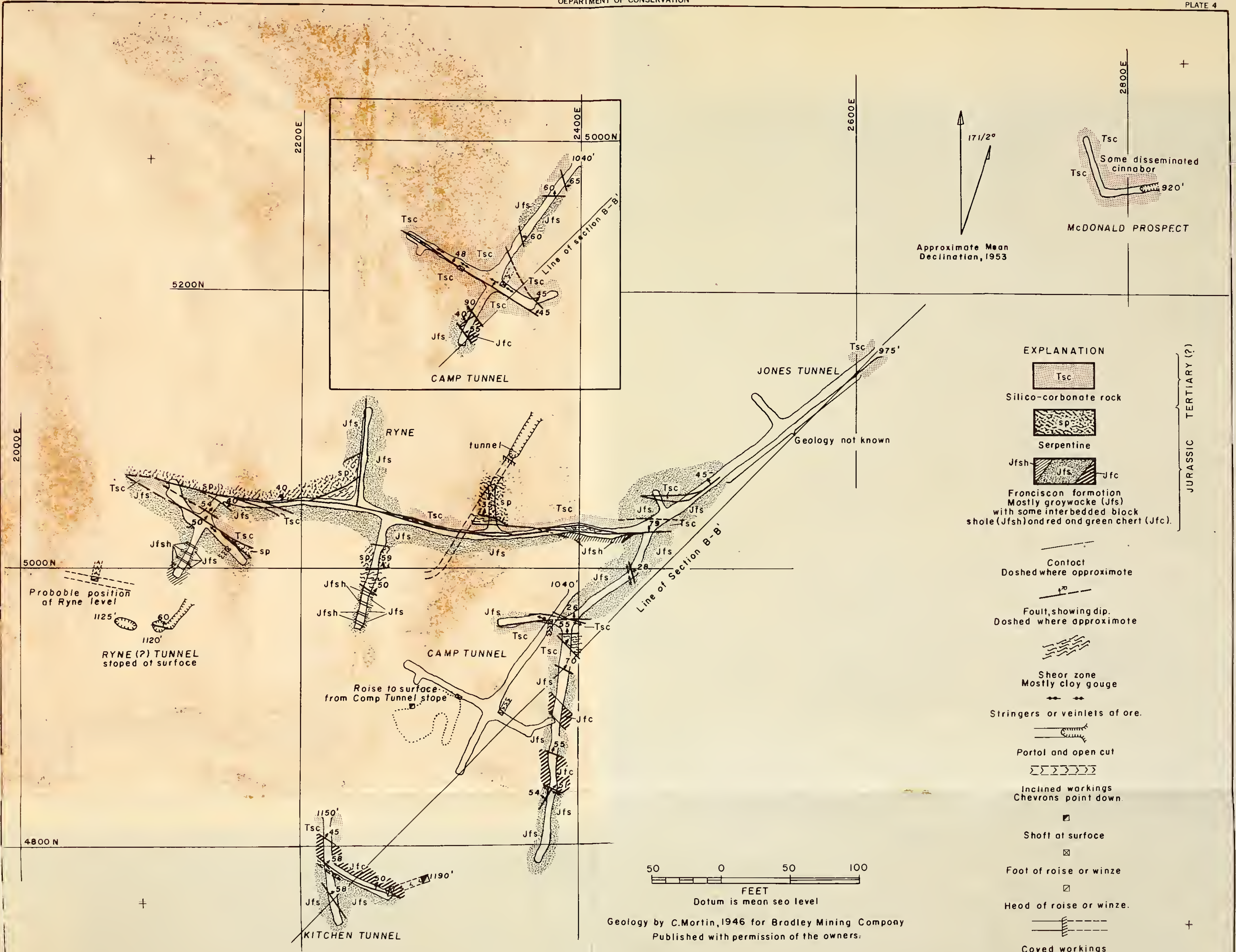
GEOLOGIC MAP AND SECTIONS OF MOUNT DIABLO, CONTRA COSTA COUNTY, CALIFORNIA



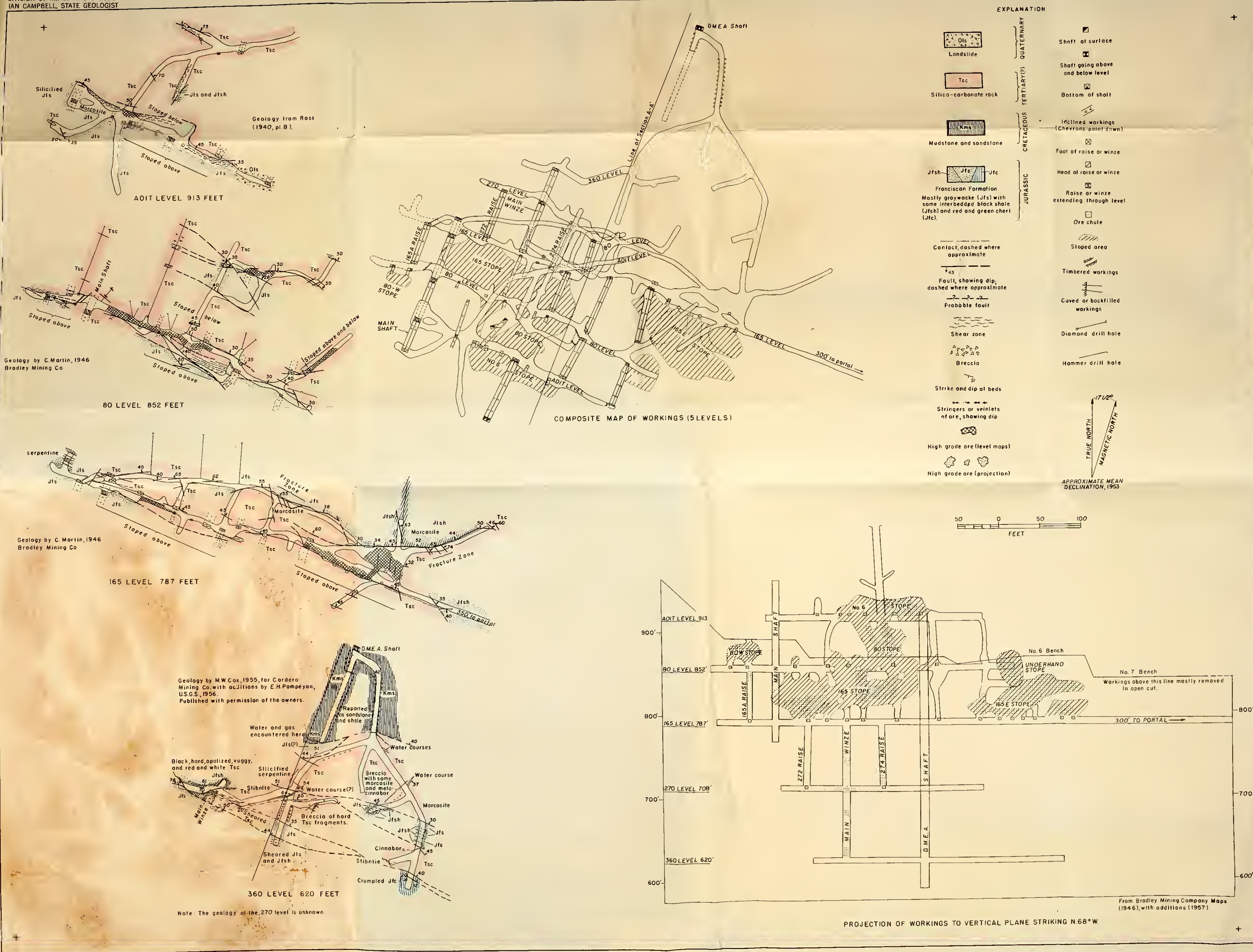
INDEX TO GEOLOGY OF MOUNT DIABLO, AFTER J.A. TAFF (1935).



GEOLOGIC MAP OF THE MOUNT DIABLO AND RYNE QUICKSILVER MINE AREAS, CONTRA COSTA COUNTY, CALIFORNIA



COMPOSITE GEOLOGIC MAP OF UNDERGROUND WORKINGS, RYNE MINE



COMPOSITE AND GEOLOGIC MAPS OF UNDERGROUND WORKINGS, MOUNT DIABLO MINE

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